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OPERATIONAL EFFECTIVENESS OF TRANSPORT AIRCRAFT

by N. N. Smirnov and I. K. Mulkidzhanov

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16. Abstract

This book discusses certain problems in the theory and practice of maintainability of transport aircraft, considering the developmental trends in their maintenance and overhaul. Factors which determine maintainability, a system of quantitative indices for estimating maintainability, and methods of performing a technical determination of the indices are analyzed. The problems of establishing the general requirements for aviation technology, methods of collecting the necessary information , and methods of evaluating maintainability of aircraft during their operation and tests are discussed.

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ANNOTATION

This book discusses certain problems in the theory and practice of maintainability of transport aircraft, considering the developmental trends in their maintenance and overhaul. Factors which determine maintainability, a system of quantitative indices for estimating maintainability, and methods of performing a technical determination of the indices are analyzed. The problems of establishing the general requirements for aviation technology, methods of collecting the necessary information, and methods of evaluating maintainability of aircraft during their operation and use are discussed.

Based on a generalization of experience acquired in repair and overhaul, the basic requirements and methods of increasing aircraft maintainability are examined. Examples are given of recommended production designs of individual aircraft units and systems.

The book is designed for engineers and technicians in plants, factories, scientific research organizations and construction offices. It will also be useful for students in aviation schools.

FOREWORD

The problems of increasing the reliability and efficiency of aircraft with a simultaneous reduction in time, labor and facilities for maintenance and overhaul are becoming increasingly urgent as air transport develops.

The successful solution of these problems, which are of great national and economic importance, is determined to a great extent by the aircraft design and, in particular, by such properties of the aircraft as adaptability or maintenance and repair operations using the most economic technological processes. With respect to the aircraft, in all technical manuals, scientific and technical literature and handbooks on problems of design and operation of aircraft equipment, this design characteristic is called maintainability.

Transport aircraft are included in the class of so-called restorable technical equipment. Even during the stage of their development, it is assumed that maintaining a given level of reliability and efficiency during operation will be achieved by taking a number of steps for maintenance and repair. This means that maintainability is not only an internal property of the aircraft construction, but also a function of its maintenance and repair system.

Increasing the maintainability of aircraft has developed comparatively recently as an independent problem, mainly in connection with the considerable complication of aircraft designs and intensification of requirements with regard to their efficient use. It is interesting to note that until quite recently only general statements with respect to ease of maintenance and repair were in most cases written in the specifications for development and manufacture of new types of machines, including aircraft; the quantitative characteristics were usually not given. Thus, the first aircraft delivery contract 50 or more years ago contained the clause: "it should be simple to handle and repair". There were several quantitative specifications for the operating characteristics, but nothing on maintainability was written in this contract [19].

Speaking about the requirements for providing maintainability, we cannot but note that the development of these requirements is one of the most important and complicated aspects of the problem being considered. When solving it, we should keep in mind that providing a high level of aircraft maintainability often goes hand-in-hand with the complexity of design. Supplementary display, built-in control, automation of malfunction search, accessibility, ease of disassembly and interchangeability of units usually complicate the design of the aircraft, and lead to an increase of its weight, cost and even to some deterioration in the reliability of individual units and systems.

Moreover, it is well known that the same type of aircraft will be characterized by a different level of maintainability in different systems of maintenance and repair. Consequently, when determining the specifications and values of the maintainability indicators, the designation and operating characteristics of the type of aircraft being considered, the characteristics of its reliability, and the selected system of maintenance and repair should be taken into account.

Each year maintainability, considered as one of the aspects of reliability, attracts increased attention of organizations and specialists working in the field of design, production and operation of aircraft. The designers, industrial technicians, and workers in operational enterprises, striving to achieve higher standards of maintainability, are seeking answers to many interesting questions. Moreover, the problems of the theory and practice of providing maintainability, methods of calculating its indicators, and methods of analysis have still not been adequately discussed in the Soviet literature.

In writing this report, the authors attempted to partially fill the existing gaps, without in any sense claiming to cover all the problems completely.

Based on the generalization of data from research, carried out at the State Scientific Research Institute for Civil Aviation, at operational and repair enterprises of civil aviation in recent years, the theoretical and practical advances in the field of maintainability are analyzed in the book.

Methodologically, the following order of arranging the material has been used.

The necessary information on utilization of aircraft is set forth in Chapter 1, the concept of maintainability is examined, and the factors which affect its level and the indicators which are used for analysis are considered.

Data on the current state and trends in development of a transport aircraft maintenance and repair system are presented in Chapter 2.

Chapter 3 contains the main concepts of the theory of maintainability. In particular, the function and elementary theorems of maintainability and its relationship to the functions of reliability and recovery, as well as methods of maintenance and repair of systems, are considered.

Important problems on the methods of determining the indicators and analyzing the level of maintainability and methods of assigning indicators in the specifications for new parts are considered in Chapter 4. Mathematical formulas for determining the operational, economic and supplementary indicators are presented; specific examples of determining these indicators are given.

Chapter 5 is devoted to problems of aircraft maintainability during their development by improving accessibility, ease of disassembly and interchangeability of maintenance and repair parts. Suggestions to improve the organization of work in the given area are also outlined.

It should be noted that some theoretical positions and practical recommendations, contained in the paper, may be related not only to aircraft, but to a number of other types of complex ted machines and technical devices. Therefore, instead of the term aircraft, others such as machine, technical device and equipment are also used in individual places of the book.

A.V. Chalov, with whose collaboration the third chapter was written, participated in writing the book.

The authors will be grateful to readers who send their responses, critical comments and wishes to the address: Izdatel'stvo Transport, Basmannyy tupik, 6a, Moscow.

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CHAPTER 1

GENERAL PROBLEMS OF THE MAINTAINABILITY OF AIRCRAFT

1. Main Concepts and Terminology

Clear definition of a considerable number of concepts and terms, related to this problem, is first required for a successful solution of the problem of aircraft maintainability. We shall present some of them here which will be most often encountered in subsequent sections of the book. /5*

Since maintainability is an integral part of reliability, the extensive use of a number of reliability terms in the book is quite understandable. These terms are used mainly in accordance with the specifications of GOST ** 13377-67 "Engineering Reliability Terms" [7].

Reliability is defined by this standard as the property of a component to perform the given functions while retaining its operational indicators within given limits for the required length of time or accrued operating time. But reliability itself is in turn characterized by a number of different properties. The main ones are dependability, durability, maintainability and storability. Let us consider each of these properties.

Dependability is understood as the property of a component to retain its efficiency during a certain accrued operating time without forced interruptions. In other words, this is the capacity of the component not to fail over the required operating period

*Numbers in the margin represent pagination in original foreign text.

**GOST = state standard.

under given conditions. With respect to aircraft, the required period is usually assumed to be the duration of a non-stop flight, trip or period between maintenance.

Durability is the property of a component to retain its efficiency up to a maximum state with the required interruptions for maintenance and repair.

The maximum state of every component may be determined on the basis of either safety requirements, or economic and other concepts. It should be stipulated in the technical documentation in every specific case.

Qualitatively, durability is evaluated as the lifetime or service life. In this case, lifetime is understood as the accrued operating time of a component until the maximum state stipulated in the technical documentation. The lifetime until first over- /6 haul, repair cycle lifetime, etc. are distinguishable.

Unlike lifetime, the service life is determined by the calendar time of operating the component until it reaches the maximum state stipulated in the technical documentation, or until "red-lived".

The term maintainability is introduced by the above GOST [7]. In this case maintainability is understood to be the property of an article to adapt to warning, detection, and correction of failures and malfunctions by maintenance and repair.

Operational effectiveness is a broader concept than maintainability. As already noted, operational effectiveness is understood to be the property of aircraft to perform a number of maintenance and repair operations using the more economical technological processes. This means that operational effectiveness, besides the properties which characterize maintainability, also includes those properties which characterize the ability of the aircraft to perform extensive operations in refuelling with liquid and gas fuel, preparation for flight, storage, and also other operations performed during operation of the aircraft.

Storability is understood as the property of a component to retain the stipulated operational indicators during and after a period of storage and transportation, determined in the technical documentation.

The term "efficiency" is used in reliability theory. Efficiency is understood as the condition of an aircraft in which it is capable of performing the given functions with parameters established by the requirements of the technical documentation (the appropriate specifications, instructions, and manuals).

The concept of efficiency should not be confused with working order. There is a considerable difference between these concepts. The concept of efficiency is usually broader than that of working order. A component, including the aircraft, may not be in working order, but may maintain its efficiency. This very important factor is taken into account when developing lists of failures and malfunctions of individual assemblies and units, with which the aircraft may continue to fly.

The concept of reliability and, consequently, of maintainability is related to the concept of failure. Failure is an event which results in disruption of efficiency.

According to the existing classification, failures may be gradual or sudden, total or partial, and may refer to the machine as a whole or to individual assemblies, units and components [1]. An event leading to disruption of efficiency, or to delay or interruption of a trip, will be considered a failure with respect to an aircraft. /7

Division of failures into gradual or sudden is arbitrary, and it is not always possible to separate one from the other. Many sudden failures are sudden only in the form of their origin, and their prediction depends on a knowledge of the changes in the technical state, level of checkability of assemblies, and available diagnostic facilities.

Sudden failure is a purely random event unlike gradual failure which is an inevitable result of natural processes of wear and aging.

The term malfunction is often used. Malfunction is understood as the condition of a component in which it does not correspond to every specification of the technical documentation. With respect to an aircraft, a malfunction means any deviation of its technical state from the norm, which does not lead to disruption of efficiency, delay or interruption of a scheduled flight. Malfunction is a broader concept than failure. Malfunctions which do not lead to failures and those (or a combination of them) which cause failures may be distinguished.

The concepts maintenance and repair are used in many terms of reliability and maintainability. Let us dwell on them in more detail.

The maintenance and repair system is understood as the combination of organizational and technical steps, carried out in a definite sequence in the operation of an aircraft to ensure its working capacity at a given efficiency.

In this definition, steps are understood as the operations which must be carried out by the specialists of operational and repair enterprises for successful operation of aircraft. They include primarily the operations of routing maintenance and repair, performed on an aircraft as preventive maintenance, as well as operations of detection and correction of sudden failures. The volume of operations Q depends on the type of aircraft, the characteristics of its dependability, durability and maintainability.

Preventive maintenance (routine maintenance and repair) means the combination of operations which may be performed on an aircraft in the required order within specific periods of time according to total number of hours flown or calendar periods, based on technical, economic and other concepts.

Preventive maintenance operations comprise the greatest part of maintenance and repair of aircraft. They have the purpose of providing trouble-free operation of the aircraft during the periods between maintenance by preventing malfunctions and failures of assemblies and units, and by retention of their technical characteristics within the limits of established tolerances. The complex of preventive maintenance operations, performed on an aircraft, /8 is sometimes called preventive action.

The preventive maintenance cycle is the period of operating the aircraft during the total number of flight hours between two mixed preventive maintenance periods — periodic forms of maintenance.

Preventive maintenance strategy denotes the combination of basic rules and procedures, whose use leads to a system of routine maintenance and repair of aircraft with respect to specific conditions of their operation.

Preventive maintenance strategy varies as a function of the purpose of the aircraft, the level of its reliability and maintainability, operating conditions, and the equipping of operational shops with production areas, means of mechanization and automation.

Routine repair is understood as operations to detect and correct sudden failures and malfunctions of units, assemblies and areas of the aircraft which occur during its operation. Routine repair operations are performed both when carrying out preventive action and during the preventive maintenance periods.

When assessing the level of maintainability of an aircraft, the technical utilization factor K_{tu} is used, which is the ratio of the total flight hours of the aircraft within a certain period of operation to the total flight time and the time of all idle periods for maintenance and repair within the operating period.

In a number of cases the term operational readiness K_r — the probability that the aircraft will be capable of operation within an arbitrarily selected moment of time during the operational maintenance periods — is used as the evaluation index. This factor is defined as the ratio of the total number of flight hours within a certain period to the sum of the flight time and the time consumed for routine repair within this same operational period.

The characteristics of failures, also called the failure rate $\omega(t)$, is also used in calculations, and assessment of maintainability. The failure rate means the average number of failures of a component per unit time, taken for the considered moment of time [7].

Parameter $\omega(t)$ is the value inverse to the mean cycles between failures $T: \omega(t) = \text{const} = \frac{1}{T}$, for the simplest failure rate, satisfying the conditions of stability, and absence of aftereffects and ordinary conditions [32]. In the general case, parameter $\omega(t)$ is a time function, although for small time segments, commensurate with mean cycles between failures T, it may be considered the simplest. Parameter $\omega(t)$ is proportional to the number of failures occurring at a given moment of time.

The mean cycles between failures T is defined as the average /9 value of accrued operating time of a component between failures. Instead of the term mean cycles between failures, the term average time of no-failure operation is used with respect to an aircraft and its systems.

The probability of no-failure operation P(t) is understood as the probability that a component will not fail within a given time interval or within the limits of a given accrued operating time.

The index probability of failure correction is also closely associated with these characteristics. It denotes the probability that the sudden failure of a component will be detected and corrected within a given time t_p.

In conclusion, let us dwell on the concept of operating expenses. Operating expenses are presently understood as those related to performing all the necessary preventive maintenance and routine repair on aircraft. These include expenditures for spare parts and materials, the wages of all personnel involved in maintenance and repair, and general production expenditures (operation of the production buildings, means of mechanization, ground equipment etc.).

2. Information on the Problem of Aircraft Utilization

The problem of increasing the efficiency of aircraft utilization is at present, one of the main problems in the operational enterprises of civil aviation. The major efforts of all specialists, working in the field of planning, production and operation of aviation equipment, are directed toward the successful solution of this problem. In this regard, all operations providing a high level of aircraft maintainability must be carried out on the basis of providing the best indices of aircraft utilization.

In this book, the problem of improving aircraft utilization is understood as that of a possible increase of the annual total flight hours and an increase of the regularity of flights with given operating expenses.

The possible total annual flight hours of an aircraft is a function of many variables. Let us consider some of them and their effect on increasing total flight hours.

The annual aircraft time reserve is approximately distributed as shown in Figure 1. A considerable fraction of time is occupied by idle time P_T in maintenance and repair, idle time P_s for different reasons in a serviceable condition, and also idle time P_p at intermediate and destination airports in completing the flight.

A registered fleet of aircraft consists of functioning machines, ready for operation, and aircraft undergoing maintenance and repair.

The number of functioning and operational aircraft is /10
characterized by the operational readiness factor K_{or}, which is

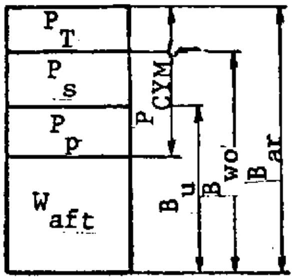


Figure 1. Enlarged structure of annual time reserve of aircraft: P_{CYM} - total idle time; P_T - idle time for maintenance and repair; P_s - idle time in a serviceable condition; P_p - idle time in performance of trips; W_{aft} - annual accrued flight time of aircraft; B_u - utilization time; B_{wo} - time in no-failure condition; and B_{ar} - annual reserve of operating time (8,760 hours).

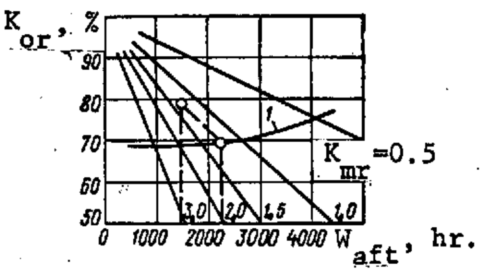


Figure 2. Dependence of coefficient K_{or} on the annual accrued flight time W_{aft} and specific idle time K_{mr}: 1 - line of maximum values of K_{or}.

the ratio of the time during which aircraft are in a functional state to the reserve of the operating time within the period under review in hours. The operational readiness factor K_{or} depends on the annual total flight time of the aircraft (the extent of annual use) W_{aft} and the coefficient, which characterizes the idle time of the aircraft during maintenance and repair, related to 1 hour of total flight time.

The dependence of K_{or} on W_{aft} and K_{mr} has the following form:

$$K_{or}=\frac{8760-W_{aft}K_{mr}}{8760}100\%, \quad (1)$$

where $K_{mr}=\frac{P_T}{W_{aft}}$ is the specific idle time during maintenance and repair, in hours per 1 hour of accrued flight time; 8,760 is the annual time reserve in hours.

It is obvious from Figure 2 that when K_{mr} is the

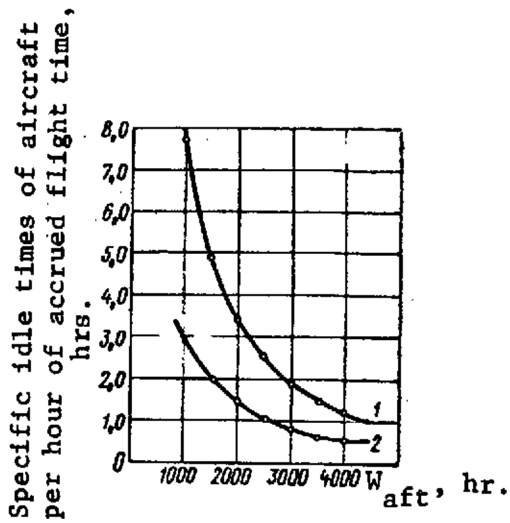


Figure 3. Dependence of specific idle times of aircraft on the annual accrued flight time (W_{aft}): 1 - total $K_{CYM}=K+K_o+K_p$; 2 - maximum permissible idle time for maintenance and repair K_{mr}.

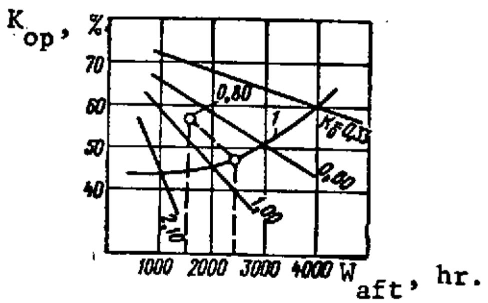


Figure 4. Dependence of coefficient K_{op} on the annual accrued flight time W_{aft} and specific idle times K_o: 1 - line of maximum values of K_{op}.

same, the readiness factor may vary as a function of the value of W_{aft} and, conversely, the value of W_{aft} with a given value of K_{or} may occur only with a decrease of the specific idle time of aircraft undergoing maintenance and repair.

It was established as a result of investigations that there is a definite dependence between the value of K_{mr} (the maximum possible value) and the annual accrued flight time of the aircraft W_{aft} (Figure 3). Substituting their maximum possible values, taken from Figure 3 for the corresponding values of W_{aft}, into formula (1) instead of K_{mr}, the dependence of the limiting minimum permissible values of K_{or} and W_{aft} (line 1 in Figure 2) may be obtained.

Technically functioning aircraft sometimes stand idle at their home airports due to an absence of cargo, waiting for scheduled takeoff, poor meteorological conditions, organizational problems, etc. The use of technically functioning aircraft, with consideration of the idle time of some of them, is characterized by the operational factor K_{op}. This factor expresses the ratio /11 of the time during which the aircraft is operational, after deduction of the idle time for the reasons indicated above, to the total reserve of operating time during the period under review in hours.

Coefficient K_{op} is almost always less than K_{or}. The following formula is recommended for calculation of K_{op}: $K_{op} = \frac{8{,}760 K_{or} - W_{aft} K_o}{8{,}760} 100\%$, where $K_o = \frac{P_s}{W_{aft}}$ is the specific idle time of the aircraft in an operating condition at the home airport, in hours per 1 hour of accrued flight time.

Coefficient K_o has an important effect on the value of K_{op} (Figure 4).

Reducing the idle time of an aircraft in operating condition leads to a sharp increase of coefficient K_{op}. When this type of idle time is absent, $K_{op}=K_{or}$.

It follows from Figure 4 that, when the value of K_o is the same, the operational factor K_{op} may vary as a function of the annual accrued flight time of the aircraft W_{aft}. However, these variations of K_{op} do not in all cases go beyond the line of its maximum values 1.

An increase of W_{aft} with a given coefficient K_{op} may occur only due to a decrease of coefficient K_o.

However, coefficients K_{or} and K_{op} still do not give a clear representation of the direct utilization of the aircraft, namely, the total hours of accrued flight time.

Therefore, it is feasible to consider yet another indicator, such as the utilization factor of the aircraft in completing the flight. As is well known, the time an aircraft spends on a trip consists of the flight time and different periods of idle times (technical preparation for the flight and idle times at intermediate and destination airports). The aircraft utilization factor during i-th trip K_{1i} is characterized by the ratio of the number of hours of accrued flight time W_{pi} to the total time the aircraft /1 spends on the trip $(W_{pi}+K_pW_{pi})$:

$$K_{1i}=\frac{W_{pi}}{W_{pi}+K_pW_{pi}},$$

where W_{pi} is the hours of accrued flight time by the aircraft in i-th trip; $K_p=\frac{P_p}{W_{aft}}$ is the specific idle time of the aircraft in completing the trip, in hours per 1 hour of accrued flight time.

In practice, the value inverse of K_1 is often used in analyzing the utilization of the aircraft during the trip.

Thus, the technical possibility of increasing the annual hours of accrued flight time of aircraft depends mainly on three factors: idle times for maintenance and repair, idle times at the home airport in operating condition, and idle times at intermediate and destination airports in completing the flights.

The dependence of the annual accrued flight time of the aircraft on these factors may be represented by the following formula:

$$W_{aft}=\frac{8760}{K_{mr}+K_o+K_p+1}.$$

It is obvious from Figure 5 that the annual accrued flight time for a registered aircraft under similar favorable conditions may be increased considerably, if these types of idle times are reduced. The role of each of these factors in increasing the efficiency of utilizing the aircraft fleet is identically important. This is especially apparent when the annual accrued flight time for an aircraft reaches 2,500 hours or more.

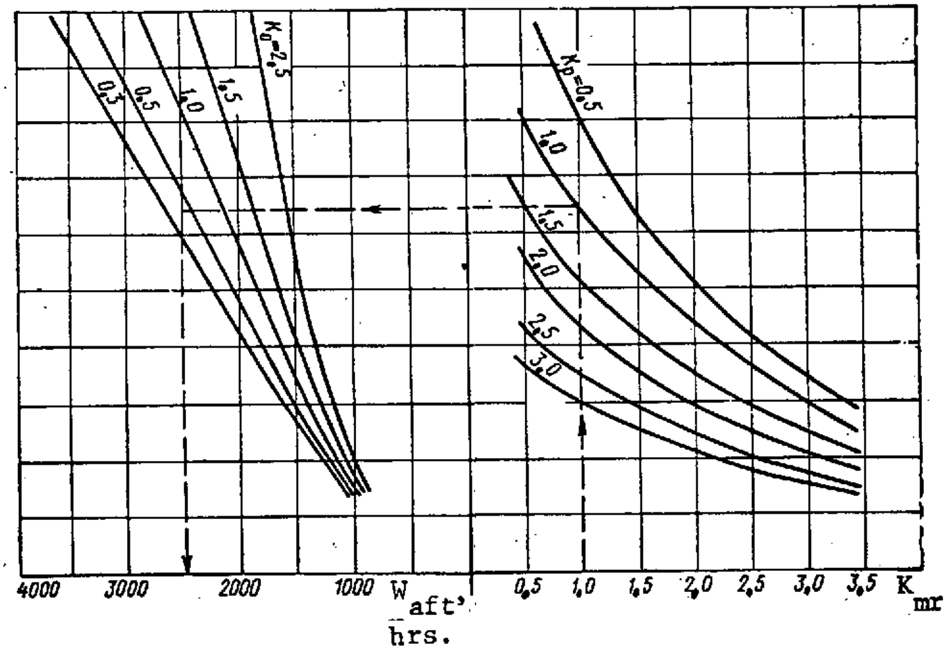


Figure 5. Nomogram for calculating the possible annual accrued flight time W_{aft} as a function of K_{mr}, K_o and K_p.

Actually, if the idle time of aircraft for maintenance and repair is sharply reduced (from K_{mr}=3 to K_{mr}=1) as a result of carrying out certain measures, but the idle times of aircraft in operating condition and after completing the flight do not change (let us assume that K_o=K_p=2), then in this case the annual accrued flight time of the aircraft may be increased by only 450 hours; but, if the idle times of an aircraft in operating condition at the home airport and after completing the flight are reduced only twofold simultaneously with a threefold reduction of idle times for maintenance and repair, the annual accrued flight time per aircraft will increase by approximately 1,100 hours.

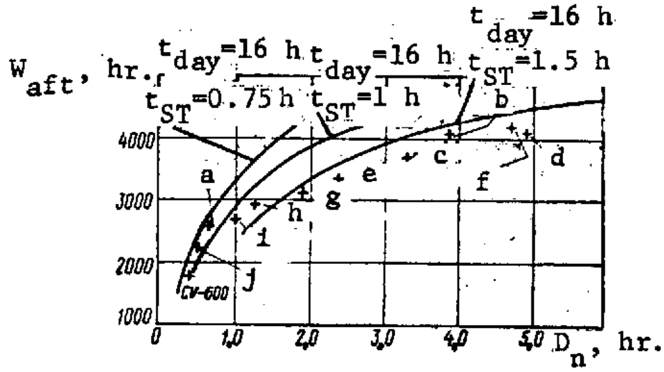


Figure 6. Dependence of possible W_{aft} on D_n (below the aircraft company is indicated after the desiganation of the type of aircraft, and the number of aircraft of a given type in the aircraft company is indicated in the parentheses):

a- FH-277, Mohawk (18); b- Boeing-707, Pan. Am. (50); c- DC-8, Pan. Am. (13); d- Boeing-707, N.W. (16); e- Boeing-720, I.A. (28); f- Boeing-707, TWA (27); g- Boeing-720, A.A. (21); h- Boeing-727, A.A. (48); i- Boeing-727, N.W. (30); j-FH-227, Ozark.

The extent of annual utilization of an aircraft W_{aft} in hours of accrued flight time may also be expressed by other parameters, in particular by the average time of non-stop flight D_n, the available daily time reserve for completing flights t_{day}, and the time of standing idle at airports between adjacent flights t_{ST}, including engine tests and taxiing around the airfield. This dependence is as follows:

$$W_{aft}=\frac{365t_{day}D_n}{D_n+t_{ST}}$$

In the given case, the possible annual accrued flight time of the aircraft is calculated by the number of complete flights, which the aircraft may perform between two points during the annual operating period (365 t_{day}). The available daily time reserve for completing flights t_{day} depends on the coefficient K_{or} and is calculated in the following manner: $t_{day}=24\ K_{or}$. The idle time of the aircraft in airports between adjacent flights t_{ST} is calculated from an analysis of the preflight and postflight preparation.

The dependence of W_{aft} on D_n with given values of t_{CYT} and t_{CT} is presented in Figure 6.

Data which characterize the actual use of certain types of foreign aircraft as a function of the average time of non-stop flight are also given in the same figure [38].

The general principle, expressed in the fact that the greater D_n, the higher W_{aft}, is obvious from Figure 6. However, the use of aircraft at the given D_n is determined to a large extent by the values of t_{day} and t_{ST}, which depend on the previously considered values of K_{mr} and K_p, respectively. /14

Thus, no matter from which point of view one approaches the study of the problem of increasing the total hours of accrued flight time by aircraft, the results are identical. The idle times caused by maintenance and repair, as well as idle time at airports between related flights in completing scheduled trips, have a considerable effect on the increase of the annual accrued flight time of aircraft.

An integral part of the problem of aircraft utilization is high flight regularity. In this case, regularity is understood as the ratio of the number of flights, completed strictly according to schedule, to the total number of scheduled flights within the same period of time. Delays and postponement of flights occur for different reasons. Cases of delays and cancellations of flights for technical reasons, i.e., those caused by failures in the aircraft and engine structure and systems, are of particular interest. The number of such cases should be reduced to a minimum.

Data on the regularity of United States aircraft flights are presented in Figure 7 [47]. These data characterize the mean level, achieved by foreign aircraft companies in other countries as well. No more than one delay for technical reasons per 100 takeoffs is usually planned for newly developed aircraft types.

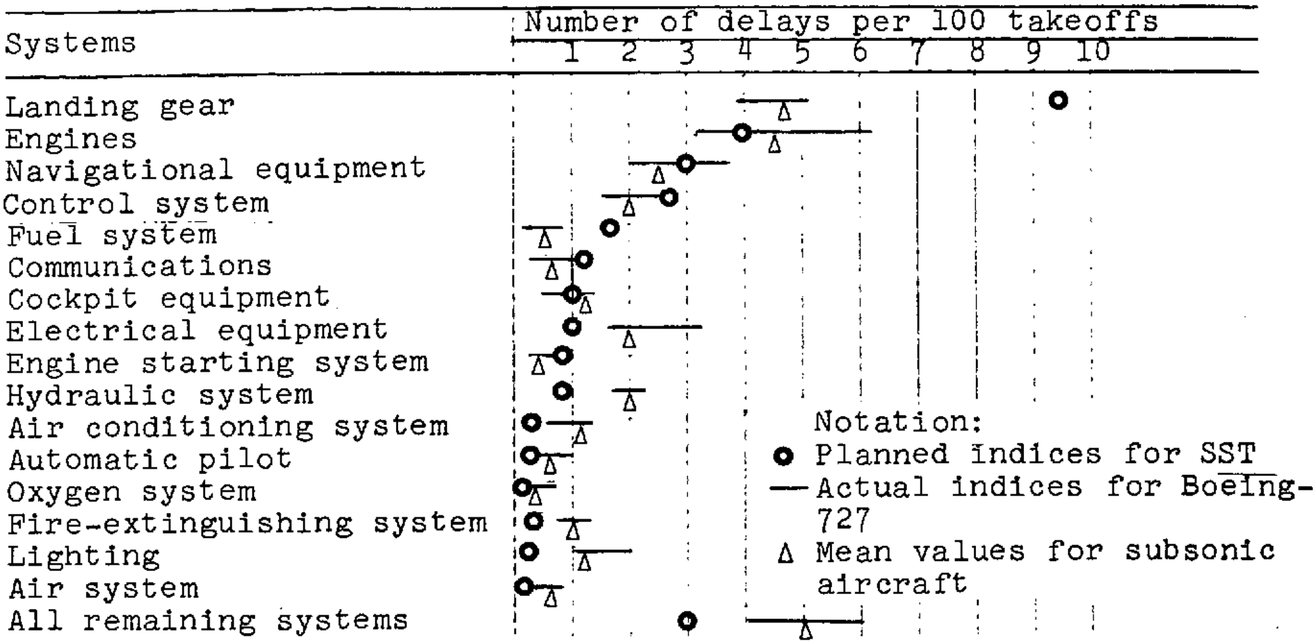


Figure 7. Data on delays of takeoffs due to technical reasons of aircraft of United States aircraft companies.

Achieving such indices of flight regularity is a very complicated problem, even if we take into account the fact that the idle time of aircraft at airports between flights is being reduced continuously. The idle time comprises 40-60 minutes for existing aircraft, and it is planned at 20-30 minutes for newly developed aircraft [36]. But the less the given idle time of an aircraft, the less is the probability of timely correction of sudden failure, arising during a flight, and the greater is the probability of a delay in takeoff.

The probability P_B of a routine takeoff by an aircraft within the established time (takeoff on time) may be written as a function of the probability P_p of no-failure operation of the units and /1
assemblies of the aircraft during the preceding flight, the

probability P_{CB} of the presence of a free team of specialists (a free unit) at the landing airport, and the probability P_y of correcting the sudden failure within time τ, not exceeding the given idle time t_d, i.e., $P_Y\{\tau \leq t_d\}$, in the following manner:

$$P_B = 1 - [(1 - P_P)(1 - P_{CB} P_y)]. \quad (2)$$

It follows from consideration of function (2) that the probability of an aircraft taking off in time P_B is determined to a great extent by the value of $P_y\{\tau \leq t_d\}$. It should be noted that an increase of the probability of timely correction of sudden failure within the given idle time $P_y\{\tau \leq t_d\}$ is an important problem in ensuring the regularity of flights, especially under conditions of reducing t_d and implementing methods of maintenance and replacement of units according to the actual technical conditions.

Approximately 70% of all apparatus, assemblies, and units may be replaced within 1 hour on the presently existing types of English aircraft, the VC-10 and BAC-111. Replacement of approximately 90% of the equipment, assemblies and units within 1 hour is planned on the newly developed Lockheed L-1011.

The Lockheed Company has determined the flight regularity of the L-1011 aircraft at 99% with a gradual increase during operation to 99.85%. This corresponds to 15 postponements of takeoffs for technical reasons per 10,000 scheduled flights.

Some of the requirements placed on the United States supersonic passenger aircraft, as part of flight regularity, utilization and maintenance, are presented in Table 1.

The mean values of similar indices for existing subsonic aircraft are given in the same table, for comparison [47].

TABLE 1.

Indicator	U.S. supersonic passenger aircraft	Modern subsonic aircraft
Flight regularity, %	99	96
Length of idle time at intermediate airports, min.	30/20	30
Length of idle time at termination airports, min.	90/30	50-90
Annual accrued flight time of aircraft, hr.	3,300	3,300
Total flying life, hr.	50,000	36,000
Expenditures for maintenance and repair per 1 hour of accrued flight time, man-hours	19.31	13.8
Average time for correcting sudden failures during a non-scheduled maintenance period, min.	30	—

One of the difficulties in solving the problem of increasing the accrued flight time and increasing the flight regularity of aircraft is that this entire operation must be conducted within /16 limited operating expenses. This is quite understandable, since successful development of air transport is possible only under conditions of a continuous decrease of transportation costs and expenditures for maintenance and repair of aircraft.

It follows from Figure 8 that the cost per 1 ton-kilometer in the aircraft companies of the member states of ICAO should be reduced by an average of 18 percent compared to the 1970 level during the period up to 1980. Maintenance and repair costs should also be reduced accordingly.

The problem of improving aircraft utilization is undoubtedly not exhausted by the data presented above. However, the necessity of developing and placing increased requirements on new types of aircraft in terms of failure rate and maintainability, which most

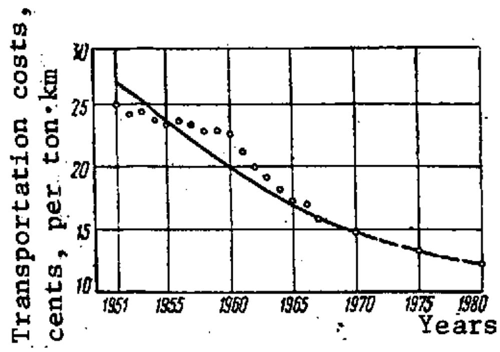


Figure 8. Variation of transportation costs of aircraft of airline companies of ICAO members (up to 1970 — actual data; from 1970 through 1980 — planned data).

completely correspond to the interests of the operating enterprises and which improve aircraft utilization, is clearly obvious from these data.

3. Development of the Problem of Maintainability and Directions of Its Investigations

The process of aircraft utilization is accompanied by continuous changes in its technical state. The irreversible processes which take place in materials change the properties of apparatus, assembly and unit components and the conditions of their operation. The probability of no-failure operation of the latter decreases in time, and malfunctions and failures develop.

The designs of modern aircraft, like any complex machines and technical devices, are not equally durable. Therefore, replacements of their apparatus, assemblies and blocks when their service life is exhausted and upon sudden failures are carried out at different times, in different types of preventive maintenance, and at different stages of preparing the machine for operation.

One of the causes of unequal strength is the non-uniform participation of the individual components of the unit in its operation. These parts, although they are made of the same material, perform different functions and undergo different stresses during operation.

The second cause of unequal strength is the fact that variation of the operating conditions has a different effect on different apparatus. /1

The third cause of unequal strength is the non-uniform nature of wear (aging) of individual components of the apparatus, manufactured from different materials.

The unequal strength of aircraft structures may be characterized in particular by the following indicators:

- distribution of the guaranteed and technical service life of apparatus, assemblies and units;
- norms of spare part consumption;
- the failure rate of different apparatus, assemblies and units

Practice shows that a considerable fraction of apparatus is replaced long before major overhaul of the aircraft, with different forms of maintenance being performed. The required periodicity of repair of multitype apparatus and assemblies of different aircraft systems is also different.

Data which characterize the number of premature replacements (based on failures) of certain apparatus and components of the English VC-10 aircraft are presented in Table 2. The number of premature replacements is given for a period corresponding to the total accrued flight time of 10,000 hours by the aircraft.

Thus, the "congenital" properties, applied during the stages of design and manufacture, are far from adequate to maintain a given level of no-failure operation during the operation of any machine, including an aircraft. The maintenance and repair system of aircraft, in particular preventive maintenance, has an important effect on dependability indicators.

TABLE 2.

Name of apparatus	Service life till overhaul, hrs.	Number of premature replacements	Accrued operating time (min-max)
Verticle gyro	According to cond.	26	262-4868
Gyro horizon	"	15	17-5526
Constant-speed drive	2500	24	210-2429
Fuel flow-gauge system:			
Sensor	3000	25	351-2466
Sensor	8000	14	78-6167
Indicator	4500	18	101-4153
Computer	According to cond.	34	86-6584
Shuttle valve in the air-conditioning system	"	63	13-541

If properly planned, preventive maintenance decreases failure rates and malfunctions, and increases the service life of aircraft. However, a specific time reserve, during which aircraft could be utilized for its purpose, is expended on preventive maintenance and repair, and the greater these time expenditures, the worse are the readiness K_r and technical utilization K_{tu} coefficients of aircraft. Moreover, a large complement of specialists, expensive equipment and monitoring-measuring apparatus are required for preventive maintenance of modern aircraft, which increases the operating expenses. /18

The readiness coefficient is calculated in [7] from the equation

$$K_r = \frac{T}{T+t_B}, \tag{3}$$

where T is the mean cycles between failures; and t_B is the mean recovery time.

In turn, the technical utilization coefficient is calculated in the following manner:

$$K_{tu} = \frac{W}{W + t_{REP} + t_{ser}}, \qquad (4)$$

where W is the total accrued operating time during the observed operating period; t_{REP} is the total idle time for repair; and t_{ser} is the total idle time for maintenance.

It follows from equations (3) and (4) that the less the average recovery time and total idle time, related to maintenance of aircraft, the higher are the readiness and technical utilization coefficients.

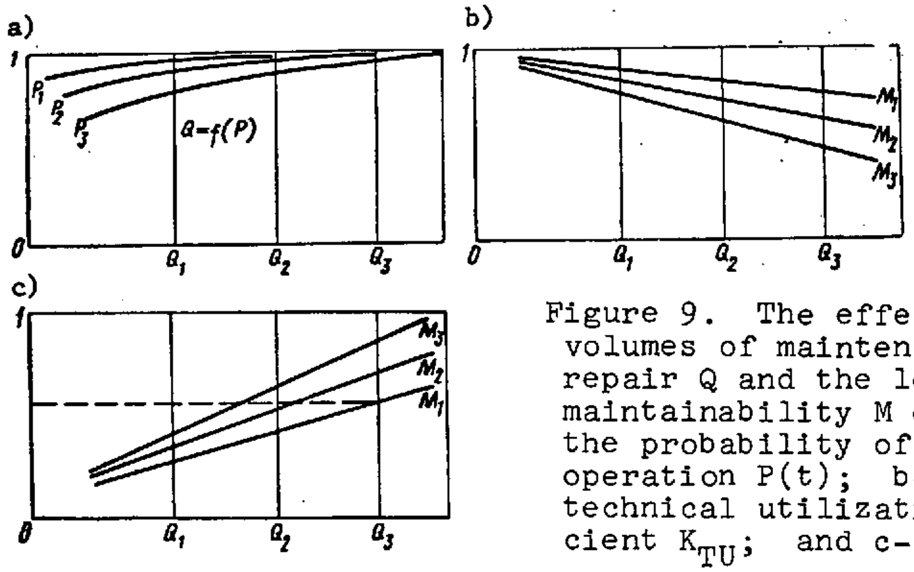


Figure 9. The effect of the volumes of maintenance and repair Q and the level of maintainability M on: a- the probability of no-failure operation P(t); b- the technical utilization coefficient K_{TU}; and c- operating expenses C.

It follows from Figure 9 that the volumes of maintenance and repair Q, calculated primarily from the probability of no-failure operation (the required level of dependability) P(t), directly affect the technical utilization coefficient K_{tu} and operating expenses C. Moreover, indices of K_{tu} and C depend to a considerable extent on the level of structural maintainability M. /19

In practice, attempts are made to reduce to the volumes of maintenance and repair without, of course, sparing the dependability indices. However, this is not always achieved everywhere. The most discernible results are achieved where a high level of aircraft structure maintainability is provided, which permits routine preventive maintenance and repair to be carried out with minimum losses of time, labor and funds.

The problem of increasing the maintainability is especially acute in relation to the continuous complication of aircraft designs and the increase of requirements to provide reliability and improved utilization.

This is quite understandable, because along with the increase in complexity of designs:

- the amount of preventive maintenance and routine repair increases considerably;
- control of the parameters is made difficult due to their diversity;
- the process of detection and correction of failures and malfunctions is complicated;
- the probability of failures appearing in relation to maintenance and repair increases [22, 25].

Moreover, more highly qualified servicing personnel and a greater number of types of devices, instruments and spare parts (SP) are required.

Failures previously occurred much more rarely due to the simplicity of the technical devices and the small number of parts making up the devices, and not as much time and labor were required to restore the efficiency of the devices. The picture has now changed sharply. The requirements on the design of numerous apparatus, assemblies and units of aircraft have become complicated year by year due to:

- increases in the intensity of operation, travel speeds and the flow of processes;
- an increased diversity of operating conditions (expansion of temperature ranges, pressures, climatic conditions etc.);
- an increase of operating precision.

The diversity of the functions performed by aircraft systems increases continuously, and due to this, the difficulties of providing their reliable operation increase sharply.

The increase in the number of components in some types of modern machines and technical devices (the growth of the complexity of machine designs) considerably outstrips the increase of their dependability indicators, which leads to a decrease of the average time of mean cycles between failures and an increase /20 of the time and facilities for performing routine repair, as well as preventive maintenance.

In a number of cases, the expenditures for maintenance and repair due to inadequate reliability and maintainability exceed by several factors the initial cost [23]: for motor vehicles — 6-8 times; tractors — 5-7 times; aircraft — 5-6 times; radar equipment — 12 times; and various machine tools — 8-10 times.

It follows from Figure 10 that the ability of servicing personnel (curve 3) has essentially changed little since the appearance of the first aircraft [46]. Man performs operations for which he is trained, with only the difference that at the beginning of the century one man performed a wide range of professions and this permitted him to service the entire aircraft, whereas one man presently performs work in a limited area, but he needs more extensive knowledge.

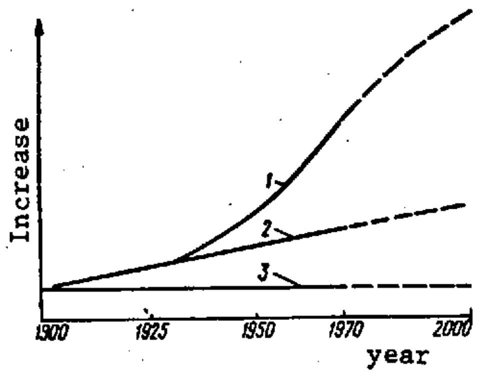


Figure 10. Graph of the changes in the technical characteristics of foreign aircraft, the complexity of their design and the abilities of servicing personnel: 1- complexity of aircraft designs; 2- technical characteristics of aircraft; 3- ability of servicing personnel.

Curve 2 denotes the changes in the technical characteristics of aircraft, such as speed, flight altitude, weight of the payload, etc. Curve 1 indicates the conplexity of aircraft designs.

The resulting divergence between these curves may be overcome only by:

- increasing the operating dependability of equipment and systems;
- increasing the maintainability of design;
- developing more effective preventive maintenance procedures.

As already noted, there is an interrelationship between the characteristics of dependability, the volume of preventive maintenance and the indicators of aircraft maintainability. Thus, a larger volume of preventive maintenance and, consequently, a higher level of maintainability are required for an aircraft with low characteristics of equipment dependability. On the other hand, aircraft with ideal characteristics of dependability do not require preventive maintenance, and the concept of maintainability loses any meaning for them.

However, these are extreme cases. At the present stage of equipment development, all complex machines require preventive maintenance, and individual apparatus, units and assemblies also have sudden failures during operation, which require timely correction. Consequently, the problem of providing a high level of maintainability of machine designs, like the problem of providing dependability, is of exceptional importance. /21

For a number of reasons, the problems of the theory and practice of maintainability have been less developed than problems of dependability. There is not yet any unanimity of views on the composition and content of basic concepts. The mathematical apparatus for the theory of maintainability has been weakly developed, and methods of providing the required properties of machine structure during their design and production have been quite inadequately investigated. The level of knowledge of these problems does not correspond to technical progress.

The main reasons for this situation may apparently include the following:

First, the maintainability of machines as a field of knowledge is presently developing at the junction of two sciences: the science of design and manufacturing technology and the science of operation of machines. But the process of developing a new science, as is well known, is always fraught with serious difficulties of methodical, theoretical, and practical importance in conducting the investigations;

Secondly, two small collectives of specialists are still involved in the given problem due to its newness;

Third, many industrial designers and technologists give basic support in their work only to providing the dependability of apparatus and assemblies, and do not consider a high level of maintainability of machines as an important problem. Moreover, the experience of the leading Soviet enterprises and foreign companies indicates that only joint development of problems of dependability and maintainability in creation of machines provides the future success of their operation.

The main trends of investigations in the field of maintainability may include the following:

- investigation of the tendencies for development of aircraft maintenance and repair systems and development of optimum procedures;
- analysis of the maintainability of existing designs of aircraft and equipment and organization of the collection of the required data;
- development of the technical requirements and recommendations to provide maintainability in designing aircraft;
- study of the theoretical aspects of maintainability, selection and justification of indicators, development of methods for calculating the estimating the maintainability during the stages of creation and testing of aircraft;
- conducting special experimental investigations and scientific work on maintainability to develop the appropriate measures for design offices, plants, and operating enterprises.

4. Factors Which Determine Maintainability /22

The concept of maintainability is not invariable for all cases. The concept is determined primarily by the purpose of the machine (component) and by the specific conditions of its operation.

Maintainability, with respect to such complicated machines as aircraft, denotes the adaptability of the design to progressive methods of maintenance and repair during operation and the ability to perform individual operations of routine repair and preventive maintenance.

Maintainability with respect to individual apparatus, assemblies and units may be characterized as their ability to check, replace or restore efficiency directly on the aircraft and the ability to repair and replace individual parts and components in repair shops outside the aircraft.

Maintainability depends on a number of factors, which must be taken into account when developing an aircraft as a function of its purpose and operating conditions. Investigations and many years practice of operating and repair enterprises indicate the two interrelated groups of factors — design-technological and operational — have a decisive effect on the level of aircraft maintainability.

Design-technological factors include accessibility, checkability, ease of disassembly, interchangeability, controllability, and the continuity of equipment and control and checking apparatus (CCA).

The group of operational factors includes the forms of organization of maintenance and repair, the condition of the production and technical base of the customer, the qualifications of service personnel, the system of providing spare parts and materials, and the completeness and quality of operational repair documentation.

Design and technological factors determine the properties of the design itself and should be taken into account when developing machines. The operational factors determine the medium in which the design properties are manifested and should be taken into account both during development and operation of aircraft.

This classification and list of factors are not the only ones possible. It is quite natural to expect other variants with some changes and additions, particularly since the theory of maintainability is still in the initial stages of its development.

It follows from Figure 11 that a design should have the properties of detectability and correctability with respect to sudden failures and should additionally have the property of preventability with respect to gradual failures. /23

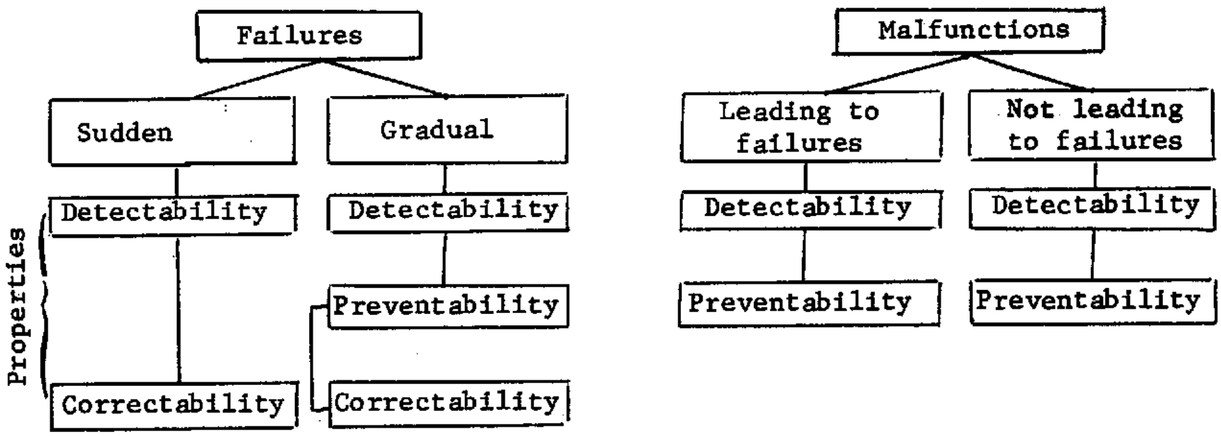


Figure 11. On the selection of factors which determine the maintainability of an aircraft.

Factors of failure detectability — checkability and continuity of CCA — primarily affect improvement of these properties and, consequently, an increase in the level of maintainability.

Factors of correctability and preventability of failures go hand in hand with factors of detectability.

They include: accessibility to individual apparatus, assemblies and units; ease of disassembly; interchangeability; and controllability. /24

Similar conclusions may be drawn from a consideration of the time distribution of routine repair of automatic electronic systems of aircraft at individual stages. The routine repair time for one of these systems is distributed in the following manner (Figure 12).

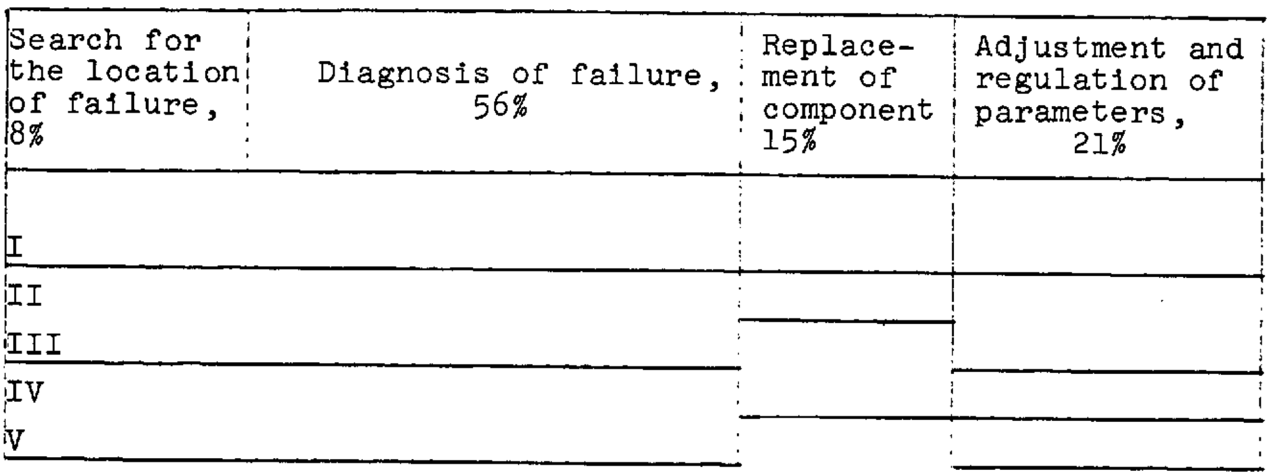


Figure 12. On distribution of the repair time by stages and determination of the composition of factors for each of them: I- accessibility; II- ease of disassembly; III- checkability; IV- interchangeability; V- continuity of CCA.

The first part, comprising about 8%, is expended on finding the location of the failure. The main portion of time (more than 50%) is expended for identification of the failed component and establishing the nature of the failure. The length of the stage of replacing the failed components is equal to 15%. The concluding part of the repair time is expended for adjustment and regulation of the system parameters for 21% of the total time.

Successful completion of these stages of repair is determined by factors of accessibility, checkability, ease of disassembly, and interchangeability of the components of the system and the continuity of CCA. Moreover, the composition of the factors varies somewhat for each of the stages.

Consideration of these factors and study of their effect on the level of maintainability are extremely important, because specific requirements and recommendations may be worked out as a result of this to increase the maintainability of aircraft during their development.

Let us dwell in detail on some of the main factors.

<u>Accessibility to the object of maintenance and repair</u>. This factor is exceptionally important to reduce the time and labor expenses both during preventive maintenance and in determining and correcting sudden failures.

The concept of accessability primarily includes the ease of work of the repairman, which is characterized by the following conditions:

- the repairman may reach with his arm to any required point in the zone of the job position, without altering his comfortable posture;
- the entire zone of the job position is clearly visible;
- the job position is not enclosed and work by touch is not excluded;
- the necessary component may be grasped and held correctly and reliably with tools.

From the view point of work convenience, three types of accessability are distinguished: excellent accessibility, when the repairman reaches the job position without fatigue, without wasting excessive effots to maintain the job posture during work; satisfactory accessibility, when the worker, reaching the job position, which is clearly visible, must assume a somewhat uncomfortable position (for example, he works with extended arms, on the knees or squatting); and inadequate accessibility, when the posture is uncomfortable and fatiguing, and the job position is determined by touch.

A different time is required to perform the same number of /25
operations, i.e., labor productivity will be different, depending on the posture which the repairman must assume during work (Figure 13). The values of labor productivity corresponding to these postures are presented in Table 3 [31].

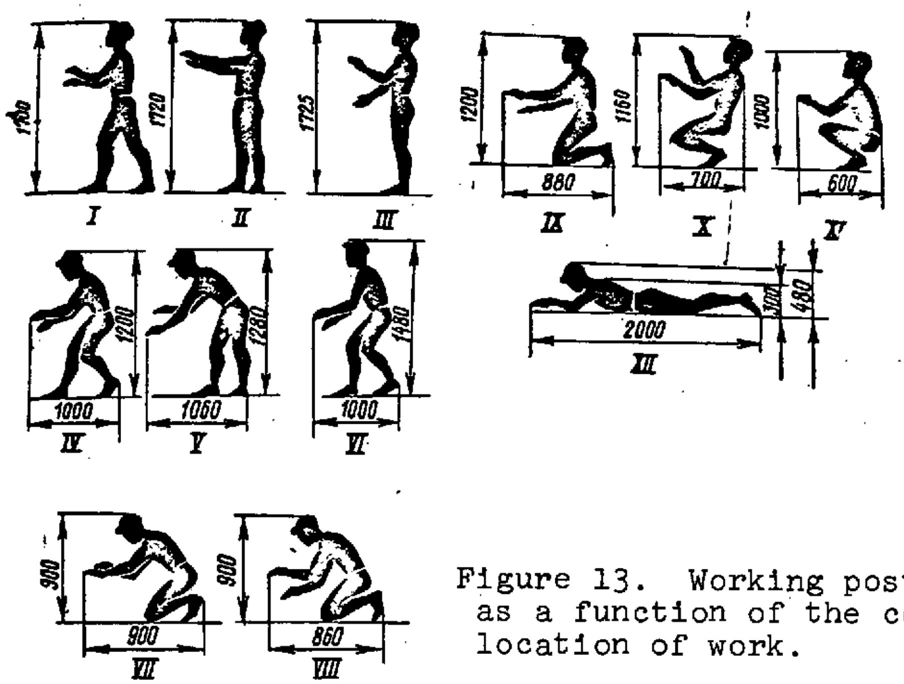


Figure 13. Working postures assumed as a function of the conditions and location of work.

However, besides the convenience of work of the repairman, accessibility also includes the suitability of the object for performing purposeful operations on maintenance and repair with minimum additional operations, or generally without them. In this case, additional operations are understood as opening and closing of panels, disassembly and assembly of equipment in an established order etc.

TABLE 3.

No. of posture	Labor productivity, %	No. of posture	Labor productivity, %
I-III	100	VII-IX	60-50
IV	95	X	67
V	75	XI	36
VI	53	XII	40-30

As aircraft designs become more complicated, the requirement for good accessibility comes more and more into conflict with the tendency to reduce the relative and absolute sizes of compartments for instruments and equipment. The increase in the number of instruments and equipment is usually accompanied by a /26
slight increase in size (Figure 14). This fact rather convincingly demonstrates the importance and urgency of the problem of providing good accessibility to the apparatus and equipment of aircraft.

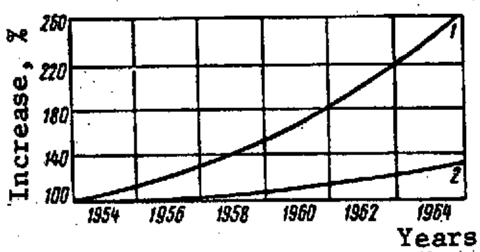


Figure 14. Increase in the complexity of aircraft equipment and increase of its size:
1- amount of equipment; 2- size of aircraft.

<u>The checkability of aircraft apparatus, units and assemblies.</u> This factor is extremely important in carrying out objective periodic inspection of the technical condition of the aircraft and finding the failed component. The factor of checkability is especially important for complicated systems, in which more than 50% of the repair time is expended on locating the position and nature of the failure. Checkability is understood as the property of a design, previously assigned and structurally

realized, to provide indirect and direct preventive maintenance inspection of the parameters of the apparatus, units and assemblies of an aircraft by various objective means and methods (primarily by automatic inspection and physical checking methods).

The importance of the problem of checking aircraft designs is determined primarily by the requirements of their reliable operation. It is natural that providing aircraft designs which can be checked by various methods and means of inspection inevitably entails additional expenses. However, these expenses pay for themselves by increasing reliability, more effective utilization of the aircraft, and reduction of expenses for maintenance and repair.

Some examples from the practice of preventive maintenance of the DC-8 and Boeing-707 aircraft of the American company United Airlines are indicative in this regard and are presented in Table 4.

It should be noted that the factor of checkability has a decisive effect on implementation of progressive methods of maintenance and repair, in particular, the method of servicing and replacement of apparatus according to its actual technical condition.

Experience in operating machines of various types shows that checkability is in many cases a feasible problem for designers and technologists. In many cases, its solution does not even require considerable complication of the design of an increase of its weight; only a knowledge of the development of failure and the determining parameters and skill in selecting the most efficient check points and means of control for each specific case are required. /27

TABLE 4.

Inspection object during preventive maintenance	Results		Objective method of inspection used
	without using objective inspection methods	using objective methods	
Piloting mechanisms	Cost of work - $15,000	Cost of work - $3,000 per man-hour expended	X-ray
Checking of assemblies instead of dismantling and disassembly	25-50 man-hours were expended	1 manhour is expended	"
Electrical connections	Hundreds of connections were inspected, cost of work - $9 per connection	Only one case of failure over a period of 3 years	"
Appearance of cracks in sparkplug openings of engine cylinders	32-man-hours expended for inspection of cylinders with the aid of optical devices	Three man-hours	Eddy-current method

Ease of disassembly of apparatus, assemblies and units. This factor should not be combined with accessibility. Components to which access is very easy, but whose replacement under operational conditions is difficult, are found on aircraft. Ease of disassembly means the suitability of the apparatus, assembly or unit for replacement with minimum expenditures of time and labor; and, since the usual method of correcting failures is replacement of the failed apparatus, the requirement of ease of disassembly is especially important to reduce the idle time of aircraft.

Ease of disassembly is determined to a great extent by the system used for attaching the apparatus and assemblies replaced during operation, the structure of connections, and the weight and dimensions of the replaceable elements.

It is necessary that all components subject to more intensive wear and aging, as well as those having the highest failure rate, be easy to disassemble.

Connections which can be rapidly disassembled, instead of ordinary nuts and bolts, should be more extensively used in a number of locations. There are also other recommendations, whose use makes it possible to improve ease of disassembly.

It should be noted that ease of disassembly of aircraft apparatus, assemblies and units is mainly a factor of maintainability when performing operations of the third stage of repair — replacement of failed components (see Figure 12).

The interchangeability of apparatus, assemblies and components. Interchangeability is understood as that property of a component (apparatus or assembly), in which any one may be installed on an aircraft without adjustment (the use of technological compensators is permitted) without selection from many /28
identical components (apparatus and assemblies).

Adjusting operations for electronic components are understood as checking (or turning if necessary) operations, because such components usually have a high geometric interchangeability, but are not always interchangeable according to output parameters.

The corresponding level of interchangeability is established as a function of the number of adjusting operations. The less the number of adjusting operations in replacing apparatus, assemblies and components, the higher is their level of interchangeability.

The factor of interchangeability is of great importance in reducing expenditure of labor and materials and in reducing the idle time of aircraft for maintenance and repair. Successful introduction of apparatus and assembly repair, and the method of replacement and repair of assemblies according to the actual technical conditions, depend primarily on this factor.

The continuity of control and checking and other ground-based equipment. Continuity in understood as the possibility of using existing control, checking, and other ground-based equipment at enterprises for maintenance, inspection and checking of the technical condition of a new type of aircraft. The more the ground-based equipment out of those available, satisfies the requirements of preventive maintenance and routine repair of a new type of aircraft, the higher is the maintainability with respect to the continuity of ground-based equipment.

This factor has a considerable effect on organization of the working area, the comfort of work of personnel, and the periods cost of maintenance and repair.

Standardization of aircraft systems, assemblies and apparatus. This factor is extremely important not only to increase the maintainability, but in solving the problems of efficient operation of aircraft as a whole. Reduction of the number of types of apparatus and assemblies for the same purpose, used on machines of the same type, considerably simplifies and reduces the cost of maintenance and repair, reduces the nomenclature of spare parts at the plant warehouses, and reduces the number of types of control and checking equipment required.

Standardization of mounting components. The number of types and dimensions of mounting components used on aircraft have a considerable effect on the level of maintainability. The number of different types of mounting components should be minimal. This makes it possible to reduce the number of required instruments and to decrease the laboriousness of maintenance and repair of aircraft.

These factors refer to the number of design and production factors. Besides these factors, the overall level of aircraft maintainability is considerably affected by: /29

- the frequency and number of scheduled operations for maintenance and repair of aircraft (including lubrication);
- the established operating life until overhaul of apparatus, assemblies and units;
- operational and technical documentation, delivered together with the aircraft;
- the system for provision of spare parts;
- the production base of operational enterprises;
- the qualifications of service personnel.

Investigations carried out by a number of organizations and enterprises and the practice of maintenance and repair of aircraft indicate that only careful consideration of all factors which affect maintainability permits industrial designers and technologists to develop aircraft which correspond completely to modern operational requirements.

5. The Indicators and Characteristics Used in Evaluation of Maintainability

For a quantitative analysis of the properties of aircraft design, which characterize its adaptability to preventive maintenance and routine repair, there must be a system of indicators which in combination would lead to:

- characterization of the main aspects of the aircraft design with regard to maintainability;
- quantitative assignment of them in technical specifications;
- comparative analysis of the level of maintainability of different classes of aircraft of the same type both during design, development and testing of prototypes, as well as in operation.

The indicators should be "sensitive" to a variation of the factors which affect the level of maintainability.

There is yet no unanimity of views in problems of selecting indicators. Different proposals with respect to selection of indicators and characteristics used in evaluating maintainability may be found in existing sources.

Thus, there are proposals with respect to the use of the following three groups of main indicators: time — for assessing the technical aspect of maintainability, i.e., for solving such problems as scheduling of repair, calculation of the required reserve of spare parts, tools and attachments (ZIP*) etc.; probabilistic — for assessing the tactical aspect; and cost — for assessing the economic aspects of maintainability.

In this case, it is suggested that the repair time be included among the temporal indicators. /30

* Translator's note: "ZIP" = Zapas chastey, Instromenta, Pnisposobeniy = Reserve of spare parts, tools and attachments.

The probabilistic indicators include:

- the probability of completing repair P_p within a given time t_d:

$$P_p\{\tau \le t_d\};$$

- the function of maintainability $F_p(t)$;
- the minimum and maximum number of specialists $n_{0\ min}$ and $n_{0\ max}$.

The group of cost factors includes the cost of repair, and relative cost of ZIP.

It is recommended in [17] that the average time of repair and the cost of maintenance be used as the main indicators.

The author of [11] recommends the use of the following indicators in calculations:

1. The probability of repair within a given period t_d.

2. Improvement of repairability (maintainability) M_Δ, expressed by the product of the probability of completing one or more maintenance operations within time t_d and the probability of one or more failures during total operating time W:

$$M_\Delta = 1 - e^{-\omega W} - e^{-\mu t_d}(1 - e^{-\omega W}),$$

where ω is the failure rate and μ is the restoration rate.

3. The readiness factors of equipment Λ_e and of completing the task Λ_M, calculated by the following formulas, are:

$$\Lambda_e = 1 - e^{-\mu t_d} + e^{-(\mu t_d + \omega W)};$$

$$\Lambda_M = \exp(-\omega W e^{-\mu t_d}).$$

In [19] the authors of a number of articles suggest using as the main indicator the "average time of restoring to operating condition," "the repair rate of components," "time of repair" etc.

The author of [5] notes that a trend has recently been observed to use indicators which characterize the temporal (operative) and economic aspects of repairability as the indicators of repairability (maintainability).

When considering the problem of maintainability indicators, it is first of all necessary to answer the question of how to define them: by random or deterministic values.

Taking into account the random nature of the factors which affect the level of maintainability, preference should be given to probabilistic indicators. However, this does not exclude /31
the possibility of using deterministic indicators, regarding them as a special case of probabilistic indicators with zero or low variance.

It is also necessary to have a clear idea of whether the maintainability indicators should be determined as a function of the internal properties of the aircraft design alone or should also take into account the conditions and nature of its operation. Obviously, it would be more proper if the level of the maintainability indicators were determined as a function of both groups of factors. This will make possible a more well-founded determination of the system of indicators for assessment and their level in intimate relation with solution of the important problems of developing methods of maintenance and repair of machines.

We feel that it is more feasible to use generalized (main) and special (additional) indicators as the indicators and maintainability characteristics. In this case generalized (main) indicators are in the form of two groups: operative and economic.

The first group of generalized indicators characterized the maintainability of an aircraft from the viewpoint of time expenditures on maintenance, repair and correction of sudden failures during operation and, consequently, the time the aircraft is in an inoperable condition. These may include:

- specific idle times for maintenance and repair K_{mr} in hours per 1 hour of accrued flight time of the aircraft. This indicator characterizes the adaptability of the aircraft to preventive maintenance, determined mainly by the dependability characteristics;
- the average time of correcting failures during the maintenance period $\bar{t}_y$. It is calculated as the mathematical anticipation of the time for correcting failures;
- the intensity of restoration μ, characterized by the number of operations completed per unit time;
- the probability of correcting the failure (restoration of efficiency) of an apparatus, assembly or unit of the aircraft $P\{\tau \leq t_d\}$ within a given time interval of the idle time of the aircraft t_d. This indicator is the probability that the random time of correcting the failure τ does not exceed the given time t_d. It characterizes the adaptability of the aircraft for routine repair during the maintenance period, related to detection and correction of sudden failures, with limited expenditures of time. In this case, the labor reserves may not be limited.

The second group of generalized indicators characterizes the maintainability of an aircraft from the viewpoint of

expenditures of labor, materials and spare parts for maintenance /32
and repair. This group of indicators includes:

- specific labor expenditures in maintenance and repair K_T in man-hours per 1 hour of accrued flight time of the aircraft. The indicator characterizes the labor expenditures, required to maintain the operational dependability of the aircraft and all its systems at a given level;
- the specific expenditures for materials and spare parts in performing the maintenance and repair K_{sp} in rubles per 1 hour of accrued flight time. This indicator characterizes the frequency of replacing apparatus, units, assemblies and components on the aircraft and the cost of their replacement.

In a number of cases, we may also use such indicators as:

- the probability of successful performance of routine repair during the maintenance period with limited labor resources T_d

$$P\{T_{T.P} \leq T_d\},$$

where $T_{T.P}$ is the random value of labor expenditure during the maintenance period;

- the probability of successful completion of routine repair during the maintenance period with limited reserves of spare parts S_d:

$$P\{S_{T.P} \leq S_d\},$$

where $S_{T.P}$ is the random value of the consumption of spare parts during the maintenance period.

Depending on the purpose of the machines and the functions performed by them, one or another group of generalized indicators may prevail. A combination of them in which the indicators will have an extreme value may be obtained in each specific case.

For example, economic indicators may emerge in first place for some types of machines with a low utilization intensity, and operative indicators — for a group of intensely used machines. However, all the above indicators are identically important for most of the machines used in the national economy.

Special (additional) indicators include those which characterize the individual aspects of the maintainability of an aircraft design. These are the coefficients of accessibility, ease of disassembly, interchangeability, checkability, continuity etc. They are utilized to evaluate factors of a constructional and organizational-technical nature, which directly affect the level of the generalized indicators.

It should be noted that these special indicators of maintainability are usually employed, easily determined and perceived /3 only for individual apparatus, assemblies and units of a complicated machine.

We feel that it is better to employ the correlation functions between the investigated processes in order to analyze the factors of the constructional and organizational-technical nature of a machine as a whole. In particular, such processes include:

- the frequency of replacing apparatus, assemblies and units on an aircraft and the time required for their replacement;
- the labor expenditure of preparation and finishing operations and the labor expenditure of entire preventive maintenance operations.

A number of other processes may also be investigated which are observed in the operation of aircraft and which are related to the maintainability of their structures.

The possibilities of using correlational analysis to evaluate the maintainability of an aircraft design will be discussed in more detail in Chapter 3.

6. Problems of the Economics of Maintainability

It is not the final goal to design a transport aircraft which is economical and simple to produce. After manufacture, an aircraft is used for many years for its primary purpose, and one of its main characteristics during this period is the operating expenses.

There is a continuous relationship between design and operating expenses. This relationship is obvious, but it is frequently not given the proper attention. When designing and manufacturing apparatus, we are satisfied with only very approximate judgments about their system of maintenance and repair and future operating expenses.

As is well known, the cost of air transportation includes expenditures for fuel and lubricants, depreciation of the aircraft and motor fleet, maintenance and repair, wages, deductions for social insurance and general production (airport) expenses. If expenditures for fuel and lubricants, crew wages, and others do not depend on the level of maintainability of an aircraft design, the expenditures for maintenance and repair are calculated to a considerable degree by how successfully the aircraft has been designed from the viewpoint of maintainability. Hence, it is possible to reduce operating expenses for maintenance and repair by proper design and manufacture of the aircraft.

The problem of the correlation of an aircraft design with the maintenance and repair specifications deserves the special attention of designers, because expenditures for these purposes comprise up to 25% of the total cost of aircraft operation. The expenditures for maintenance and repair during the entire operating life of a gas-turbine aircraft exceed the initial cost by five-six times.

When considering the different design versions in order to select the best of them for mass production, and also when evaluating finished aircraft of different types, it is expedient to use the criterion of the economy of design in production and operation K_e. /34

The criterion K_e may be calculated as the ratio of total expenditures for production, maintenance and repair per 1 hour of accrued flight time to the weight of the aircraft structure in tons:

$$K_e = \frac{C_H + \sum_{i=1}^{N} C_{pi} + C_T A}{AG}, \qquad (5)$$

where C_H is the cost of a new aircraft, in rubles; C_{pi} is the cost of the i-th major overhaul of the aircraft, in rubles; N is the number of major overhauls during the total operating life; C_T is the cost of preventive maintenance and routine repair of the aircraft per 1 hour of accrued flight time, in rubles/hr; A is the total operating life of the aircraft, in hours; and G is the weight of the aircraft structure, in tons.

The criterion of design economy, calculated by formula (5), has the following value for certain tyeps of foreign aircraft (according to 1968 data [38]):

Type of aircraft	Boeing-707-300	DC-8-50	Boeing-720	Boeing-727	N-262
Weight of structure, tons	57	56	50.3	37	6
K_e, dollars/hr-tons	6.9	6.5	7.0	7.8	8.3

It should be noted that the values of criterion K_e are different for aircraft with a different structural weight. It is understandable that the smaller the aircraft and the less its weight, the higher is K_e.

One of the current problems is the development of standardized values of indicator K_e as a function of the weight of the aircraft structure G. Having such norms in the future, the design economy of different types of aircraft may be estimated comparatively easily.

The main methods of increasing the design economy of an aircraft are:

- an increase of the total operating life of the aircraft A;
- an increase of the operating life until the first overhaul and between periods of overhaul and, consequently, a reduction in the number of overhauls N per total operating life A;

An increase in the dependability and maintainability of designs. /35

The economic effectiveness of any of the technological steps carried out by the design office, manufacturing plant or operational enterprise to reduce the cost and to increase the service life of components should be calculated on the basis of the total national-economic effect.

The indicator of design economy may in many cases be improved by a certain increase of production expenses, caused by the necessity of using higher quality and more expensive materials, more labor-consuming reinforcing and finishing processes, complication of production techniques, and increasing the number of design and finishing operations. Let us cite a specific example to confirm the feasibility of using the given measures.

Let us assume that the initial cost of an arbitrary aircraft is 1 million rubles, where the total operating life under given operational conditions is 20,000 hours, the overhaul period is every 2,000 hours of accrued flight time with average expenditures for preventive maintenance and routine repair of 60 and for major overhaul of 70 rubles/hour of accrued flight time. The fraction of initial cost per 1 hour of accrued flight time is 50 rubles for the total operating life of the aircraft.

Let us now assume that a number of effective measures to increase the wear-resistance of components, the service life of apparatus and assemblies of the aircraft, to improve its design and technological development, with consideration of the requirements of maintenance and overhaul, increased the initial cost of the aircraft by 20%, i.e., up to 1.2 million rubles. But as a result, the total operating life of the aircraft was increased to 25,000 hours and the overhaul period — to every 5,000 hours of accrued flight time, with average expenditures for preventive maintenance and routine repair of 40 and for major overhaul — of 30 rubles/hour of accrued flight time. The fraction of the initial cost will be 48 rubles/hour of accrued flight time. This will save 62 rubles per 1 hour of accrued flight time. The saving for 25,000 hours of accrued flight time comprises more than 1.5 million rubles. Moreover, losses due to idle times for maintenance and repair are reduced. The total savings in operation will in this case exceed the additional initial expenditures by increasing the service life, dependability, and maintainability by at least seven-eight times.

In conclusion, let us dwell on the problem of calculating the additional production expenditures for design and manufacture of aircraft, justified by improvement of the design maintainability.

Let us assume that, as a result of carrying out a number of design and technological measures, the maintainability of the aircraft design is improved so that this reduces the labor expenditure of preventive maintenance and routine repair by 20%. Accordingly, the wages of the engineering and technical service workers per 1 hour of accrued flight time are reduced. The approximate structure of the expenditures for servicing the aircraft is shown below.

Average expenditures for maintenance of aircraft (rubles and kopecks) per 1 arbitrary unit of maintenance /36

	1969	1970
Wages with deductions	16.91	16.99
Expenditures for materials and spare parts	16.77	16.56
General production expenditures	4.85	4.75
Total	38.53	38.30

Consequently, a reduction of maintenance labor by 20% leads to a decrease of total expenditures by 8-10%.

Having calculated the difference in expenditures for maintenance per 1 hour of accrued flight time of the initial aircraft version and with improved maintainability, we can calculate the annual saving E and find the value of justified additional production expenditures K_{pe}.

It is recommended in [4] that the value of K_{pe} be calculated by using the values of the specific additional production expenditures in rubles $\overline{K}_{pe}$, based on reduction of the maintenance labor by 1% due to improvement of the maintainability of the aircraft design (Figure 15).

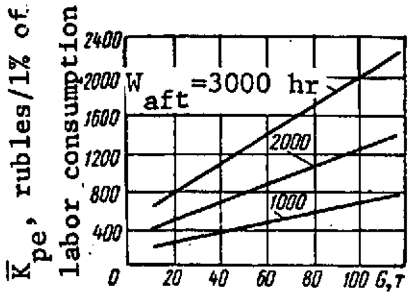


Figure 15. Dependence of specific operating expenditures $\bar{K}_{pe}$ on the weight of an aircraft G and on its annual accrued flight time W_{aft}.

Continuing our example for an aircraft with a design weight of G=60 tons and an annual accrued flight time of W_{aft}=2,000 hours, with the aid of Figure 15, we find $\bar{K}_{pe}$=850 rubles per 1% of labor reduction. Consequently, in our case $K_{pe}=\bar{K}_{pe}\,n\%=850\cdot20=17,000$ rubles.

The annual savings for operating expenses per aircraft is [4] $E=0.382\,K_{pe}=0.382\cdot17,000=6,494$ rubles.

The foregoing must be taken into account when developing new types of aircraft and apparatus or when performing modifications on existing designs.

The values of a number of aircraft maintainability indicators depend not only on the design properties, but also on the maintenance and repair system used. In the given case, the maintenance and repair system is a type of medium in which the properties, characterizing its adaptability for prevention, detection and correction of all possible failures and malfunctions, included in the aircraft design, are revealed.

The design of an aircraft and its maintenance and repair system are closely interrelated. Successful development of a maintenance and repair system is possible only if there is a certain improvement of the aircraft design with respect to maintainability, and improvement of the design of each new type of aircraft should be carried out with total consideration of the characteristics of the planned maintenance and repair system. /3

This must be taken into account when solving all problems of providing aircraft maintainability, in particular, those such as the basis of specifications, selection of indicators, methods of calculating them, and methods of analysis.

CHAPTER 2

CHARACTERISTICS OF AIRCRAFT MAINTENANCE AND REPAIR SYSTEMS

1. Main Assumptions and Stages of Development

The maintenance and repair of modern passenger aircraft is a complicated and laborious process. When developing maintenance and repair systems, a number of problems related to the required level of reliability, safety and flight regularity under the best technical and economic indicators of the activity of enterprises, are solved.

The entire complex of measures on maintenance and repair of aircraft may conditionally be divided into two groups:

- routine preventive maintenance, related mainly to prevention of failures and malfunctions;
- operations to detect and correct sudden failures (routine repair).

There may be different relationships between these groups of operations, depending on the criterion of the optimum conditions and strategy of performing preventive maintenance. But in any case the main requirement placed on the maintenance and repair system as a whole consists in the fact that the maximum probability is provided that the aircraft will be operable at a certain arbitrary moment of time and will perform the given mission, and expenditures of labor, time and resources to maintain the aircraft in an operating condition will be minimum. When developing /
methods of maintenance and repair, the most attention should be devoted to preventive maintenance operations with respect to transport aircraft.

Depending on the purpose of the aircraft, routine preventive maintenance operations may be designated according to achievement of a definite accrued operating time in hours, according to achievement of established calendar periods, and according to both of the named indicators.

Preventive maintenance according to accrued operating time is usually designated for aircraft and technical devices which operate intensively without prolonged breaks.

Preventive maintenance according to calendar periods is established for machines and technical devices with a low use intensity or which are in a monitoring mode. The given type of preventive maintenance is to prevent failures caused by aging phenomena.

Combined preventive maintenance (according to accrued operating time and according to calendar periods) is used mainly for machines and technical devices with a nonuniform operational intensity in time.

Two main procedures — scheduled and mixed — are distinguished according to periods of performing preventive maintenance operations.

The scheduled procedure includes preventive maintenance operations strictly within a specific accrued operating time regardless of the number of failures observed during this period (Figure 16 a).

Preventive maintenance operations in the mixed procedure are performed either within a specific accrued operating time, if there have been no failures during the maintenance period, or at the moment of correcting the failure which has occurred during the maintenance period. In the latter case, the period of performing routine preventive maintenance is calculated from the moment of completing unscheduled preventive maintenance (Figure 16 b).

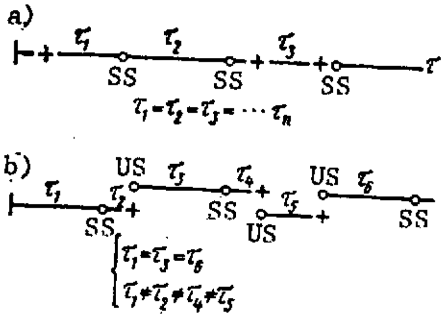


Figure 16. Procedures of preventive maintenance operations according to periods of performance:

a- scheduled; b- mixed procedure (SS - scheduled; US - unscheduled preventive maintenance).

Notation: o = preventive maintenance; + = random failure.

Each of the procedures has its own advantages and disadvantages. Thus, in the case of the scheduled procedure, the times when the machine is brought in for preventive maintenance are predetermined. This permits precise scheduling of work, provision of a uniform load on the service personnel, and preparation of the sets of spare parts and apparatus beforehand. At the same time forced idle times of machines due to /39
random failures during the maintenance period are not used here at all for performing preventive maintenance operations.

In the mixed procedure, forced idle time of machines for random failures is fully employed to perform preventive maintenance operations. In a number of cases, this is a considerable advantage. However, with this procedure, the times when machines are brought in for preventive maintenance are not determined precisely, which creates difficulties in scheduling and preparation of equipment.

The scheduled procedure for performing preventive maintenance operations has been widely used for civil aviation aircraft.

Three procedures are distinguished according to the nature of operations performed during preventive maintenance:

1. Preventive maintenance with forced replacement of apparatus and units after they have exhausted their design operating life;

2. Preventive maintenance with replacement of apparatus and units according to their actual technical condition;

3. Preventive maintenance with the combined method of replacement of apparatus and units.

All these types of preventive maintenance operations include inspection, adjustments, repairs and replacements of apparatus. The main difference is in the extent of inspecting the technical condition of the machines and the number of replacements of units and apparatus.

Thus, in the first procedure, the number of inspections is usually small, replacement of the greater part of apparatus and units occurs in forced order according to when they exhaust their established operating periods prior to overhaul. Only an insignificant portion of replacements is accomplished from the results of inspection.

The second procedure is characterized by the use of a considerable number of inspections of the technical condition of the machines. Such a procedure is often called preventive maintenance according to parameters. The number of adjustments, repair, and replacement operations of equipment is determined only from the results of inspection.

The third procedure is a combination of the first two. In the given procedure, one part of the machine (primarily those which do not have controllable parameters and means of inspection) is replaced due to being worn out, and the other, which is inspected periodically during operation — according to the actual technical condition.

The third procedure of preventive maintenance with the combined method of replacing apparatus and units is used more extensively at the operating enterprises of civil aviation.

It should be noted that the previously employed methods of maintenance and repair of machines are unstable. Methods of maintenance and repair are also improving as aviation technology develops, as operating experience is accumulated, and as the production base is improved.

Investigating the data on development of preventive mainte- /40
nance and repair methods of Soviet and foreign aircraft over the past 30 years, it is easy to note the presence of several interrelated stages. There were three such stages, in particular, in U.S. aircraft companies [45]. Let us consider the more distinguishing features of aircraft maintenance and repair methods employed at each of these stages.

The first stage began prior to World War II. The main type of aircraft at that time was the DC-3. The method of separate maintenance and repair was then employed. Aircraft maintenance included daily and simple periodic types of inspection within specific calendar periods. Major overhaul of an aircraft was performed within a single process. In this case, the machine was completely disassembled, inspected, and repaired at the points of damage and was reassembled. After completion of this set of operations, the aircraft could essentially be operated until the next major overhaul without performing any type of complicated repair operations when performing preventive maintenance.

The second stage began after World War II with the introduction of such aircraft as the Constellation, DC-6, DC-7 etc.

The methods of maintenance and repair of these types of aircraft became more sophisticated. The operational and technical documentation was worked out more completely and comprehensively. As the utilization of aircraft improved, the airline companies changed over to scheduled maintenance and repair as a function of the hours of accrued flight time.

The airline companies sought newer and more effective methods of maintenance and repair. The method of performing major overhaul of aircraft during a single process was replaced by most airline companies at this stage by a step-by-step method, known as "progressive repair."

The third stage began with introduction of gas-turbine aircraft. During this period, the airline companies devoted a great deal of attention to the further improvement of the operational and technical documentation, organization of preventive maintenance, provision of spare parts and organization of finishing operations on aircraft. The methods of step-by-step (progressive) repair were used by almost all large aircraft companies. The method of replacement and repair of aircraft systems and special equipment according to the actual technical condition was recognized by most firms and aircraft companies of different countries and found practical application.

The beginning of a fourth stage should be expected in the future. More extensive use of methods of replacement and repair of apparatus according to the actual technical condition is anticipated here. It is assumed that this will be achieved by using means and methods of automatic inspection, investigation /41 of the types of failures and analysis of their effect on the efficiency and reliability of systems, as well as improvement of the maintainability of aircraft designs. Performance of adjustment operations and replacement of apparatus will be accomplished primarily by programs of the "TARAN" type ("test and replace if necessary") and "ITCAN" type ("inspect, test and repair as necessary"), which are partially being employed at correct as VC-10, BAC-111, Trident, DC-9, Boeing-727 and other aircraft.

These stages and trends of development of aircraft maintenance and repair systems are typical for the aircraft companies of both the United States and other countries.

Let us dwell in more detail on the problems of organization and the methods used for maintenance and repair of modern aircraft.

2. Aircraft Preventive Maintenance

Characteristics of Maintenance Conditions

Preventive maintenance operations are carried out according to the available regulations and specifications for each type of aircraft. These documents determine the type of maintenance of the aircraft.

The regulations are the main document which determines the extent and periodicity of preventive maintenance operations on the airframe, power plants, and special equipment of the aircraft.

The specifications are the document which determines the sequence, procedures, technical conditions and labor expended on the performance of individual operations.

Regulations and specifications, as well as changes and supplements to them, are confirmed and put into effect by the Administration of the Aviation Engineering Service of the Ministry of Civil Aviation after coordination with the appropriate design offices.

Operative and periodic types of preventive maintenance have been established for civil aviation aircraft. They are performed on the aircraft in a specific sequence during the established repair period (Figure 17).

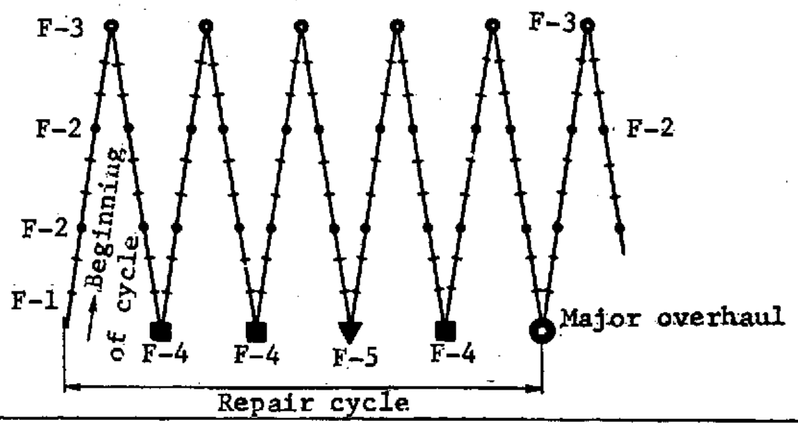
Operative types of maintenance	Periodic types of maintenance and repair
1. Preflight 2. During brief stand-still 3. Postflight	

Figure 17. Typical graph of performing different types of periodic maintenance on an aircraft during the repair cycle.

Operative types of maintenance include preflight and post-flight servicing, as well as maintenance during brief standstills of the aircraft.

When performing each of the operative types of preventive maintenance, the main purpose is to ascertain the operating condition of the aircraft and its readiness for flight by external inspection, and also to detect and correct any sudden failures of individual apparatus and assemblies which occur. Each type /42 of operative preventive maintenance consists of inspection and maintenance operations and those to ensure takeoff or layover.

Performance of inspection and servicing operations during any type of operative maintenance ensures the readiness of the aircraft for flight for 12 hours.

Operations to ensure takeoff are performed immediately prior to takeoff, and operations to provide a standstill are performed in cases when the aircraft is delivered from the crew to the air maintenance base (AMB).

Preflight maintenance in performed immediately prior to takeoff, if it is carried out more than 12 hours after performance of any type of operative preventive maintenance, and also immediately after performing preventive maintenance. Preflight maintenance consists of external and internal inspections of the aircraft; checking of the functioning of individual systems, apparatus and instruments; heating or cooling of the air in the cockpits; checking of the amount of fuel, oil, water, special fluids and refueling if necessary if there is a flight delay.

Preventive maintenance during brief layover is performed immediately after each landing of the aircraft at the airport, if a more complicated type of maintenance is not required according to the hours of accrued flight time. This maintenance includes external inspection of the aircraft during preflight /43 servicing, inspection and cleaning of the cabins, galley, and toilets, and heating or cooling of the air in the cabins, topping off with fuel, oil, and water, and also correcting malfunctions noted by the crew during flight.

Postflight maintenance is performed immediately after completing the trip, if a more complicated type of periodic maintenance is not required according to the hours of accrued flight time. In this case, a more careful inspection of the fuselage skin, wings, tail assembly, engine cowlings, power plant and landing gear apparatus is carried out on the aircraft then during a brief standstill; the first stages of the compressor and the last stages of the engine turbine are inspected; the seats, tables, equipment, locks and latches of the access doors, the emergency hatch covers and cabin windows; and the cabins and toilets are cleaned. The aircraft is supplied with fuel, oil and special fluids, and recharged with oxygen, nitrogen and air according to the mission for the next flight.

Periodic forms of maintenance are characterized first by a considerably greater volume of operations performed in comparison with operative types, and secondly, by strictly determined periodicity of performing them, the basis of which is the number of hours of accrued flight time of the aircraft.

For most types of gas-turbine aircraft, the regulations stipulate the following periodic forms of maintenance: form No. 1 (F-1) — every 50 ± 10 hours of accrued flight time, form No. 2 (F-2) — 200 ± 20, form No. 3 (F-3) — 600 ± 20, form No. 4 (F-4) — 1,200 $\pm^{20}_{220}$, and form No. 5 (F-5) — 3,000-3,600 hours of accrued flight time.

When performing the periodic forms of maintenance, the main goal is to determine the operability of the aircraft and its readiness to continue flights by close inspection and control of the technical condition, and also to detect and correct malfunctions of apparatus and units which occur at different stages of their development in order to prevent gradual failures during operation.

The amounts of work in the same forms of maintenance of a specific type of aircraft are equal to each other. Each subsequent form of maintenance includes operations stipulated by the preceding form, as well as specific operations inherent only to this form. Thus, in operations according to form No. 3, operations according to forms Nos. 2 and 1 are also carried out.

When replacing the engines for any reason on an aircraft, the form of maintenance which is required according to the accrued flight time is carried out, and the operations directly related to replacement of the engines are performed.

In accordance with regulations, all operations of periodic forms of maintenance are subject to operational inspection for the quality and completeness of performance. Inspection /44 is carried out by an engineer of the Technical Control Section (TCS), the duty engineer and the chief technician. The degree of participation of each of them in operational control is indicated in the graph "control" of the regulations for each type of aircraft. The TCS engineer performs the final analysis of the technical condition and inspection of the aircraft after completing the periodic form of maintenance.

Operations of any periodic form of maintenance are divided into preliminary, main and final.

Preliminary operations essentially coincide with those to provide a standstill, which are carried out in operative types of maintenance.

The main types are grouped according to individual aircraft systems: power plants, airframe, landing gear, steering system, hydraulic system, air system, altimeter equipment, radio equipment, electrical equipment, instrumentation, oxygen equipment and housekeeping equipment, sanitation facilities, water system, and flight recorders. The volume of main operations and the labor expenditure are increasing due to the increase in the number of the forms of maintenance.

Final operations consist of refueling and recharging the systems with compressed gases, locking of the rudder and aileron controls, cleaning of the working position, and closing and, in /45 the case of possible icing, covering of the aircraft.

Regulations for maintenance of all types of aircraft are being perfected continuously. During the initial period of aircraft operation, this improvement is directed toward reducing the number of operations and increasing the periodicity of performing them. For aging types of aircraft, improvement includes mainly correction of individual adjusting operations with established periodicity of performing the different forms of maintenance.

The results of many years of operation of collectives of the State Scientific Research Institute of Civil Aviation, design offices and operational enterprises of civil aviation to improve the maintenance regulations for Il-18, Tu-104, An-10 and An-12 aircraft are shown in Figure 18.

It follows from Figure 18 that three stages may be distinguished in improving the regulations. The first of them was completed by 1962. Periodic forms of maintenance every 500 and 1,000 hours of accrued flight time were introduced in 1962 into the new regulations for technical servicing of these types of aircraft. This made it possible to reduce the idle times and labor expenditures for maintenance, and also created a real basis for successful solution of the problem of increasing the repair cycles of aircraft.

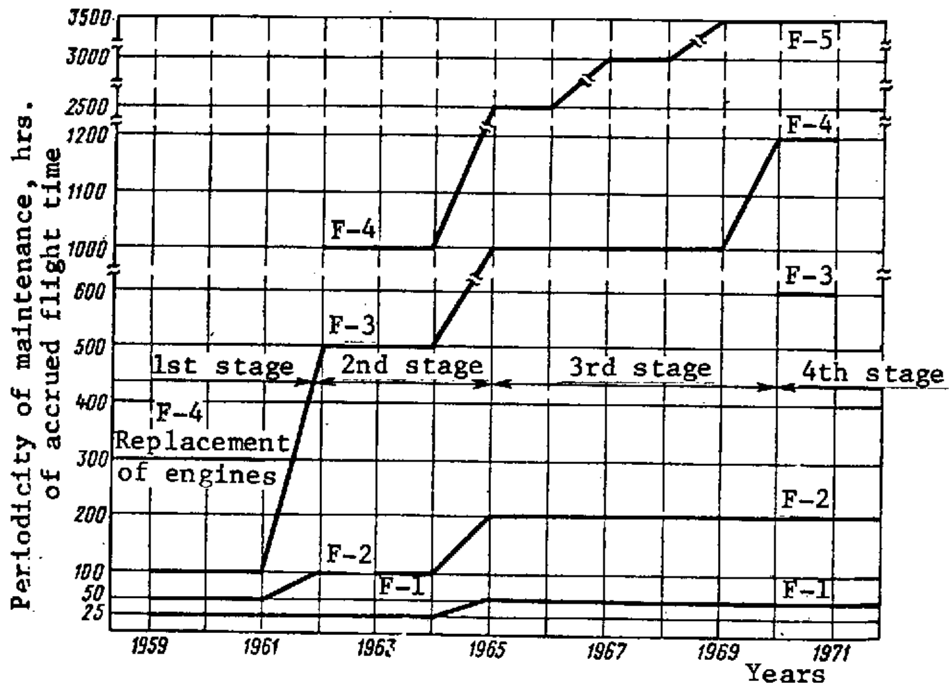


Figure 18. Changes in the periodicity of performing the different types of maintenance of the Il-18, Tu-104, An-10 and An-12 aircraft during operation.

The periodicity of performing the types of maintenance doubled in the regulations for 1965, namely: the 25-hour form is performed every 50 hours, the 100-hour — every 200, and the 500-hour — every 1,000 hours of accrued flight time. A new periodic form, which must be performed every 2,000-3,000 hours of accrued flight time (depending on the type of aircraft), was introduced into the regulations with establishment of a repair cycle of 4,000-5,000 hours of accrued flight time.

And finally, the following changes were introduced into the 1969 regulations: a 600-hour form of maintenance was introduced; the 1,000-hour form is performed every 1,200, and the 2,000-3,000-hour form is performed every 3,000-3,600 hours of accrued flight time.

The maintenance regulations for other types of aircraft are being improved in a similar manner.

Organization of Maintenance

Aircraft maintenance is performed at the air maintenance bases (AMB) of operational enterprises. Many of these bases have large hangars, equipped with docks and the required facilities for mechanization and CCA. Organization of maintenance at bases, as well as the regulations, are being improved continuously.

Periodic forms of aircraft maintenance are performed by the method of specialization, based on division of labor between teams, with simultaneous performance of operations in different zones of the aircraft. In this method, all operations are divided into several groups, each of which is performed by one /46
specialized team.

The number of teams depends on the volume of operations and the presence of specialists, but the number of members in the teams is determined by the amount of labor involved in the processes. The members of each team specialize in performing individual operations, although any team member should know how to perform all operations assigned to a team.

The step-by-step method of performing periodic forms of maintenance has been successfully used in recent years in many operational enterprises. The essence of the step-by-step method is that the total volume of the periodic form of maintenance is divided into several parts — stages. Performance of individual stages is scheduled for the time of day or for those days of weeks when the aircraft are not being used for scheduled flights. This makes it possible, without reducing reliability, to considerably increase the operational readiness of the aircraft fleet and to reduce losses due to the aircraft standing idle all day for maintenance.

Since the step-by-step method of maintenance is accompanied by a certain increase of total labor expenditure due to repetition of part of the preparation and finishing operations, a study of the specific conditions is performed prior to its implementation.

Division of the periodic form into individual stages is accomplished as a function of the flight schedule, the shift-operating schedule of the AMB, the specialization and numbers of the team members in periodic forms of maintenance, as well as on the volume of work of each form.

The operations have shown that the use of the step-by-step method of maintenance is based on the following principles:

- each stage should consist of final maintenance of one or several systems of the aircraft in the periodic form and maintenance of the remaining systems in the operations carried out during brief standstills;
- the number of stages, as well as the number of systems and the combination of systems of the aircraft, included in each stage, are determined by the operational enterprise on the basis of specific operating conditions;

- performance of periodic forms of maintenance by the step-by-step method should be carried out within the limits established for each form of allowances.

The established allowances for performing the periodic forms of maintenance are usually very small, and this makes it difficult in a number of cases to use the step-by-step method. Naturally, the problem arises of extending the allowances due to their differentiation for individual groups of operations contained in a certain stage (Figure 19). Solution of this problem would permit considerable expansion of the total allowance for performance of a certain form of the regulation without a loss of aircraft reliability.

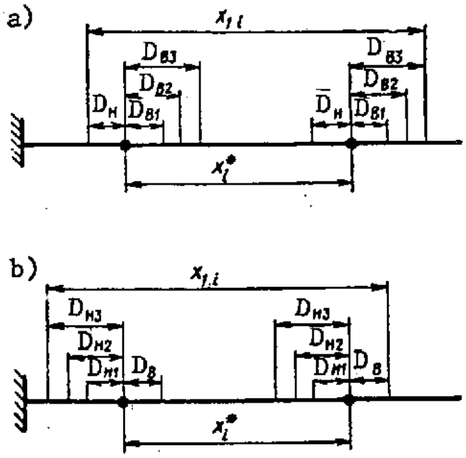


Figure 19. Diagram of establishing differentiated allowances for performance of individual groups of operations:
a- with unchanged low allowance D_H; b- with unchanged high allowance D_B.

Network methods of scheduling and control (NSC) are finding ever broader application in aircraft maintenance. /47
They permit extensive consideration of the most difficult element of any plan — time, and make it possible to accomplish objective inspection and to more specifically control the performance of different operations [18].

Network graphs are employed in network scheduling and control, which make it possible to:

- clearly and vividly display the structure of all operations which comprise the production process, and to establish their interrelationships;

- rationally distribute the volume of operations between executors, compile a schedule for their performance within an established period with a guarantee of the required probability of timely performance of the task;
- determination and mobilization of time reserves, labor reserves and material resources due to optimum organization of production;
- simplification of the operations and concentration of the attention of the executors and management on those operations which may delay timely completion of maintenance, i.e., which make it possible to control production according to the control principle of the "leading link."

The experience of using NSC at air maintenance bases indicates that the idle times of aircraft for maintenance may be reduced considerably due to efficient readjustment of the maintenance process, redistribution of the work force and concentration of the attention of the engineering and technical staff on "critical operations," even without using additional reserves.

Finally, the theory of mass maintenance is finding application in the operation of the AMB in organization and scheduling of preventive maintenance [18].

Using this theory, which takes into account the effect of random factors, many problems of organizing the processes of aircraft maintenance are solved at a higher level, the requirements for preventive maintenance are investigated, the idle times of aircraft are scheduled, and the different methods of organizing periodic forms of maintenance are compared.

Labor Expenditures and Idle Times of Aircraft During Maintenance /48

The efficiency of organizing aircraft maintenance at a given level of reliability and maintainability is determined mainly by the indicators of labor expenditures and idle times.

The norms of labor expenditures effective in 1970 for performance of different types of maintenance of certain types of aircraft are presented in Table 5.

TABLE 5.

Type of maintenance	Labor expenditures, man-hours					
	Type of aircraft					
	Il-18	Tu-104	An-10	An-24	Tu-124	Yak-40
Operative:						
preflight	24	18	25	12	11	7,5
brief stand-still	15	11	16	7	7,5	4
postflight	25	21	26	13	14,5	9,5
Periodic:						
every 50 hours of accrued flight time	86	58	96	42	45	35
" 100 "	—	—	—	51	58	48
" 200 "	370	300	390	172	170	120
" 600 "	450	350	470	220	225	190
" 1200 "	830	760	850	370	490	245
Replacement of engines	520	350	570	280	260	200

These norms were calculated for civil aviation enterprises which have hangars equipped with all the equipment necessary for performing maintenance of all types, stipulated by the regulations. The indicated labor expenditures for operative types of maintenance performed outside enclosures are effective only for temperatures above -5°C. At temperatures of -5°C or below, these norms are corrected with the aid of correction factors, the values of which are given below.

CORRECTION FACTORS FOR DIFFERENT ATMOSPHERIC TEMPERATURE

From −5°C to −20°C	1,15
» −21°C » −35°C	1,25
» −36°C » −45°C	1,5
» −46°C to −50°C	1,75
Below −51°C	2,0

The index of specific labor expenditures for maintenance and repair of aircraft K_T in man-hours per hour of accrued flight time has recently been used often when performing exploratory work.

This index is being reduced from year to year due to improvement of regulations and organization of maintenance, an increase of the repair cycles of aircraft, engines and apparatus (Figure 20).

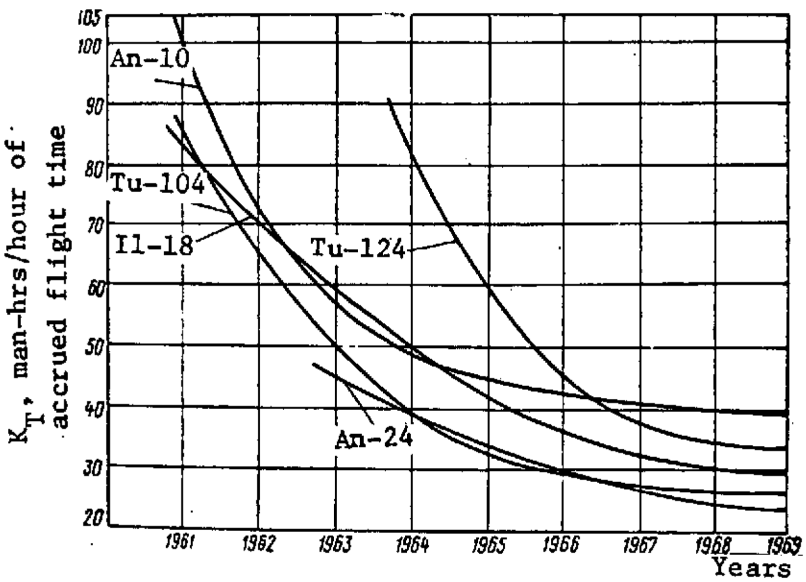


Figure 20. Change of specific labor expenditures for maintenance and repair of aircraft during the period 1961-1969.

The idle times of aircraft are an important indicator of the effectiveness of maintenance systems. Standard values of aircraft idle times in periodic forms of maintenance have not been established at present. The average values of scheduled idle times of certain types of aircraft for maintenance (without consideration of waiting time) are characterized by the following data according to the calculated data of operational enterprises for 1969 (Table 6). Nighttime interruptions are also included in the indicated scheduled idle times.

TABLE 6.

Type of maintenance	Average values of scheduled idle times, hrs.				
	Type of aircraft				
	Il-18	Tu-104	An-10	An-24	Tu-124
Periodic:					
after 50 hrs. of accrd. flight time	6	7	7	4	7
" 100 "	—	—	—	21	18
" 200 "	34	38	57	36	28
" 600 "	70	88	109	53	46
" 1200 "	86	104	126	86	83
Replacement of engines	71	46	37	92	32

A very valuable characteristic when analyzing idle times is the distribution of their duraction (Figure 21).

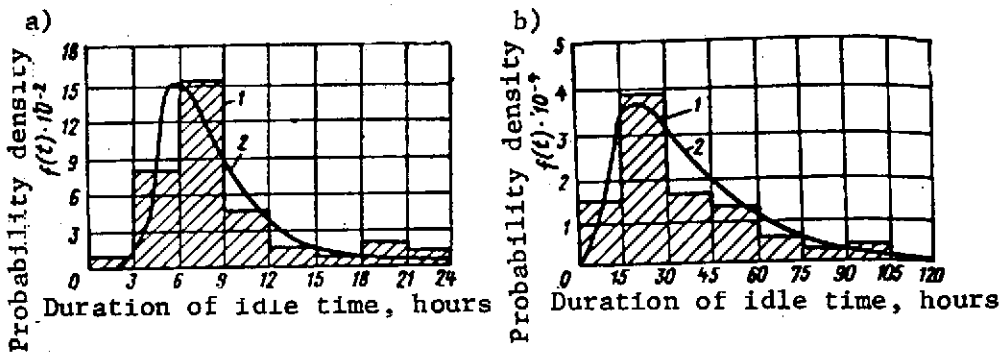


Figure 21. Examples of distribution of the duration of idle times of Il-18 aircraft during maintenance:

a- after 50 hours of accrued flight time; b- after 200 hours of accrued flight time;

1- experimental data; 2- theoretical distribution curve.

As already noted, the idle times for different types of maintenance should be reduced according to an increase in the annual accrued flight time of an aircraft. Thus, the required reduction of idle times in hours during different types of maintenance of Tu-104 aircraft, including the waiting time, is shown in Table 7 as a function of the annual accrued flight time per aircraft.

TABLE 7.

Type of maintenance	Maximum possible idle time of aircraft (hrs.) in annual accrued flight time, hrs.			
	2000	2500	3000	4000
Operative:				
preflight	2,5	2,0	1,75	1,2
brief standstill	1,5	1,0	0,75	0,6
postflight	2,0	1,5	1,00	0,8
Periodic:				
after 50 hours of accrued flight time	4,5	3,5	3,0	2,2
" 200 "	35,0	25,0	15,0	10,0
" 600 "	72,0	60,0	40,0	28,0
" 1200 "	90,0	72,0	48,0	36,0

These values of the idle times according to the types of maintenance were determined by calculations. The dependence of the specific idle times for maintenance and repair on the annual hours of accrued flight time (see Figure 3), as well as the ratio between the idle times in individual types of maintenance and repair, established at the civil aviation enterprises, were /50 also used in the calculations.

Observation of the established idle times for maintenance /51 and repair, especially with an annual accrued flight time of

3,000-4,000 hours, is a complicated problem. Under these conditions, the factor of the adaptability of designs to progressive methods of servicing and repair, which provide the required reduction of labor and resources expenditures, is of special importance.

Foreign Practice of Aircraft Maintenance

The methods and forms of organizing maintenance in foreign aircraft companies are selected with consideration of the number of aircraft, the given accrued flight time per aircraft, the flight routes, the seasonality of shipments and the technical capacities of the aircraft companies.

The basis for development of maintenance methods is the recommendations of the manufacturing companies on the extent and periods of performing regular operations as a function of hours of accrued flight time, as well as according to the service life of the airframe equipment, finished components, and systems apparatus.

Labor expenditures and idle times for preventive maintenance for the VC-10 and Boeing-707 aircraft in the English aircraft company BOAC are as follows (Table 8).

The regulations regarding high labor expenditure along with maintenance operations include considerable amounts of repair operations and aircraft modifications.

The American aircraft company United Airlines uses the following maintenance system for DC-8 aircraft [39].

Preflight inspection, performed prior to each flight. Its purpose is to determine the overall working condition of the aircraft and its readiness for takeoff.

TABLE 8.

Type of maintenance	VC-10 aircraft		Boeing-707 aircraft	
	Duration of idle time, hours	Labor expenditures, man-hours	Duration of idle time, hours	Labor expenditures, man-hours
Transit for aircraft flying through	2.5	5.8	2.5	5.4
Transit at base	8	100	8	75
Transit at base No. 2:				
every 220 hrs. of accrued flight time	8	166	—	—
" 325 "	—	—	8	172
Regulation of aver. labor:				
every 650 hrs. of accrued flight time	72	2,166	48	1,500
Regulation of high labor:				
every 4200 hrs. of accrued flight time	17 days	13,690	—	—
" 4500 "	—	—	10 days	14,790

In-transit maintenance, performed at intermediate airports. /52
In this case the locations on the aircraft where fuel or oil leaks, as well as damage or stresses may appear, are inspected. The maintenance time comprises approximately 1 man-hour.

In-transit maintenance, carried out at the destination airport every 25 hours of accrued flight time. In addition to operations of the preceding maintenance, the condition of the input and output devices of the engines, landing gear and tires is checked. The time is approximately 4 man-hours.

Low maintenance requirements, carried out every 100-125 hours of accrued flight time. Besides the in-transit maintenance every 25 hours of accrued flight time, this type of maintenance includes checking the systems, and ground inspection of all sections of the aircraft surface to determine any damages to the rivets, weld seams, buckling of the skin etc. The maintenance time comprises 6 to 12 man-hours.

Average maintenance requirements, carried out every 575-625 hours of accrued flight time. In this type of maintenance, besides the external inspection, all zones of the aircraft are checked carefully to detect early symptoms of failure. Special attention is given to those sections where symptoms of malfunctions were previously detected. The time varies within the range of 400-500 man-hours.

Finally, there is also a system of high maintenance requirements, carried out every 7,000 hours of accrued flight time. Each of these maintenance operations is essentially the average repair time of the DC-8 aircraft.

Italian airline company Alitalia observes the following system of preventive maintenance of DC-8 aircraft.

Preflight inspection. No more than 30 minutes is required for this, requiring about 2 man-hours.

Regulation O is performed after every 180 hours of accrued flight time. The length of the idle time comprises 4 hours (mainly at night) and labor expenditures are about 200 man-hours.

Regulation D is performed after every 500 hours of accrued flight time. The aircraft is in the shop for 32-36 hours and the labor expenditures required to perform the regulation comprise 900 man-hours.

Regulation DC is performed after every 3,500-4,000 hours of accrued flight time. The idle time is up to 7 days, and labor expenditures vary between 2,000 to 3,000 man-hours.

Regulation E is performed after 8,000-9,000 hours of accrued flight time. The idle time of the aircraft reaches 30 days (when working a single shift). Labor expenditures comprise approximately 15,000 man-hours.

The distinguishing feature of the maintenance systems used abroad is that a different frequency of performing the operations is assigned for the same type of aircraft in different airline companies. This is vividly illustrated by the data presented in Table 9 for the Boeing-707, DC-8 and Caravelle aircraft.

TABLE 9.

Airline company (country)	Frequency, hrs. of accrued flight time
	Boeing 707
Sabena (Belgium)	75, 300, 600, 1200, 3000
Air India	135, 400, 800, 1600, 2500, 5000
BOAC (England)	150, 300, 4000
Lufthansa (FRG)	35, 115, 315, 4000
Quantas (Australia)	85, 160, 450, 4000
	DC-8
Alitalia (Italy)	180, 500, 4000, 8000
Swissair (Switzerland)	100, 330, 4000
SAS (Scandinavia)	110, 325, 4300
Iberia (Spain)	200, 400, 800, 1200, 2400, 4800, 7200
JAL (Japan)	120, 450, 5000
	Caravelle
Alitalia (Italy)	110, 350, 3000, 6000
TAP (Portugal)	75, 225, 675, 1350, 3000
SAS (Scandinavia)	75, 250, 3500
Swissair (Switzerland)	85, 275, 3500
Finnair (Finland)	150, 450, 900
Yugoslavian Air Transport	60, 250, 3000

The difference in the frequency of maintenance of aircraft is explained primarily by the technical capabilities of the airline companies, as well as by the number of aircraft of a given type available to them.

Aircraft apparatus and units are replaced at various times based on the established operating life until overhaul. However, in order to reduce the time for preventive maintenance of aircraft and for convenience in scheduling, replacements of certain apparatus and units are combined with routine forms of maintenance.

The frequency of aircraft maintenance varies as operating experience is accumulated. Firms and airline companies work constantly to increase the frequency of maintenance, considering this to be one of the radical methods of reducing expenditures of time and resources. Thus, the English airline company BEA changed the maintenance frequency of the Viscount aircraft five times, continuously increasing it, over an operating period of /54
10 years from 1954 through 1964. The other English airline company BOAC increased the maintenance frequency of the Britannia aircraft several times. Lufthansa (FRG) also increased the maintenance frequency several times during the period 1964-1967 (Figure 22).

It should be noted that the designs of modern passenger aircraft were developed with extensive utilization of the "fail-safe" principle and have a high maintainability. This contributes to even more successful operations on increasing the frequency of maintenance and overhaul. For example, the frequency for the VC-10 aircraft is characterized by the following data (Table 10).

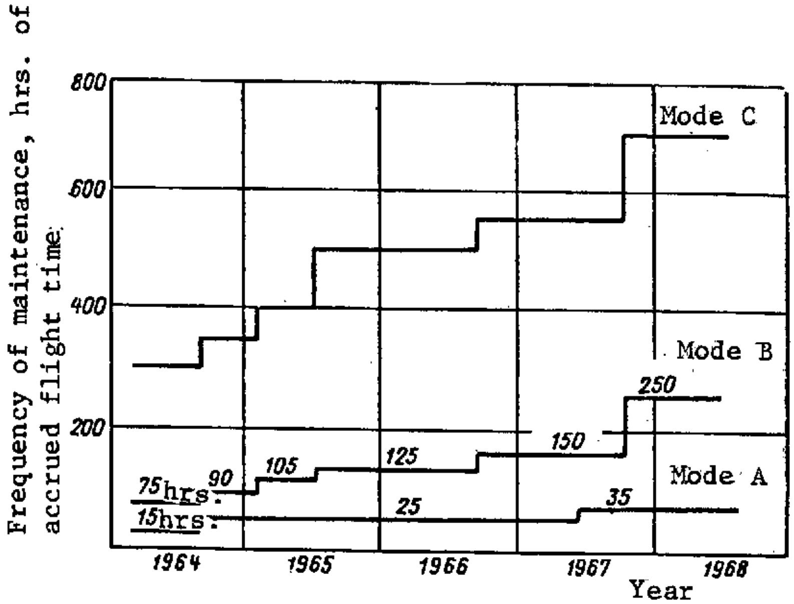


Figure 22. Variation in frequency of performing the forms of maintenance of the Boeing-727 aircraft.

TABLE 10.

Type of maintenance	Frequency, hours of accrued flight time		
	Upon entering operational service	After 1 year of operation	After 2 years of operation
In-transit maintenance during idle periods	100	200	300
Main form	300	500	600
Principal form of maintenance and repair	4,000	5,000	6,000

Even with a quick analysis of the data presented in Table 10, it is easy to note the comparatively high increase in the maintenance frequency of a given type of aircraft. That which was done to increase the frequency of maintenance on the VC-10 aircraft over a period of 2 years usually required 6-7 years on other types of aircraft.

Something must be said about the methods used to increase the frequency of maintenance. Main emphasis is usually given to the operational experience and the results of processing statistical data. As an example, the program of two stages of increasing the frequency of maintenance of the DC-9 aircraft is presented in Table 11.

TABLE 11.

Type of mainte-nance	Stage	Possible increase of frequency, hrs. of accrued flight time	Volume and conditions of performing maintenance with satisfactory results
A	1 2	From 20 to 25 " 25 " 30	100 times on no more than one aircraft
B	1 2	" 100 " 150 " 150 " 190	30 times on no more than two aircraft
C	1 2	" 450 " 650 " 650 " 800	10 times on no more than three aircraft
D	1 2	" 3,500 " 5,800 " 5,800 " 7,500	No less than on 10% of the aircraft fleet (a minimum of one aircraft)
E	1 2	" 10,000 " 16,000 " 16,000 " 32,000	No less than on 10% of the aircraft fleet (a minimum of one aircraft)

Disposition of the service personnel in performing the routine forms of maintenance is accomplished according to the zone principle. For this, the aircraft structure is divided into a number of zones, and the organization of operations, specialization of the personnel, and the technical documentation are worked out with respect to these zones.

The advantage of the zone principle of maintenance of complicated aviation equipment is in the more complete utilization of the labor force on the aircraft, a reduction in the volume of the preparation and finishing operations, creation of the best working conditions, an increase of responsibility of the personnel, and a reduction of the maintenance time (Figure 23).

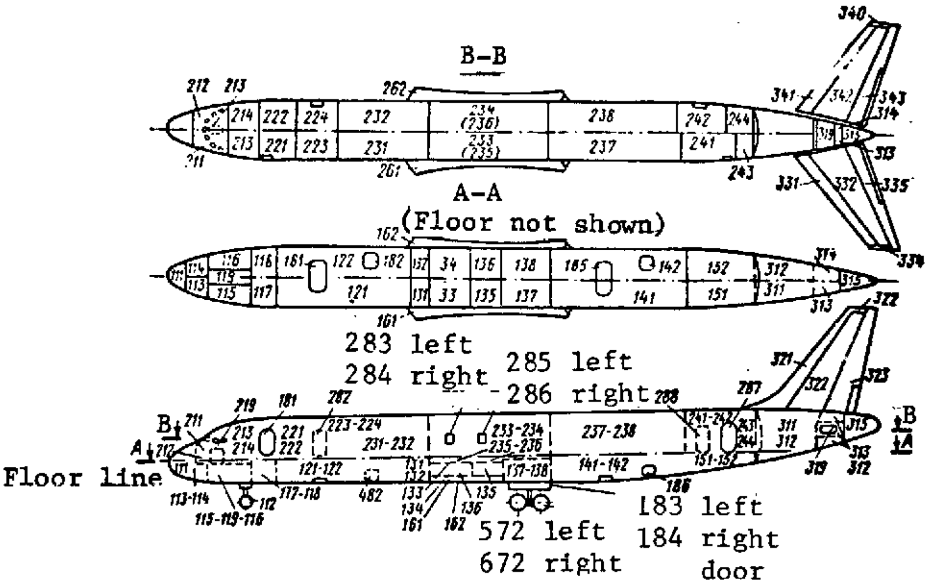


Figure 23. Example of dividing the DC-8 aircraft into zones.

A specific system is used to designate the zones. The number for any zone consists of three figures. The first figure denotes the large portion of the aircraft, and the second and third figures — the smaller parts and assemblies.

Fuselage zones, located below the floor level of the passenger cabin, are usually assigned numbers in the 100 series, and zones located above the floor level — series 200. Numbers of series 300 are assigned to zones of the tail section of the fuselage and the tail assembly, numbers of series 400 — to zones of the /5 engine cowlings, and numbers of series 500 and 600 — to zones of the left and right parts of the wing, respectively. For example, the number 300 denotes the general tail portion of the aircraft, number 320 — the vertical tail, and number 323 — the rudder.

All hatches for inspection of the structure, located in a certain zone of the aircraft, are denoted by the number of this zone and a corresponding letter (Figure 24). This creates a simple and sufficiently accurate system of notation of all access hatches of the aircraft, which helps to rapidly locate any of them when performing maintenance regulation operations.

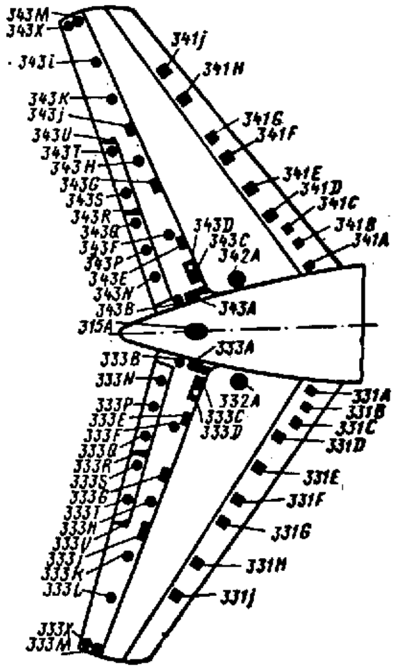


Figure 24. Notation of access holes on the stabilizer of the DC-8 aircraft.

Problems of organizing the routine forms of maintenance are not solved in the same way everywhere. Routine maintenance in many airline companies is carried out in one procedure with two-to-three-shift operation of the shops. However, there are other airline companies which, attempting to make the load of the shops uniform and to provide a daily accrued flight time of approximately 10-12 hours per aircraft, are developing and introducing methods for carrying out the periodic forms of maintenance by units (the method of equal labor expenditure, the method of "continuous" maintenance etc.).

There are no essential differences in organizing the operative types of maintenance in foreign airline companies. Among the most important problems which are being resolved in this case are a reduction of aircraft idle time at intermediate airports to perform in-transit maintenance and high regularity of takeoffs.

3. Aircraft Overhaul

/

The efficiency of aircraft utilization and the level of operational expenditures depend to a great extent on the organization of the repair operations and on the quality of repair.

Whereas the main purpose of maintenance is to carry out inspection and to prevent gradual and sudden failures, the purpose of overhaul is to restore the technical state of the aircraft according to the overhaul specifications. The latter is achieved by disassembly, extensive inspection, and replacement or repair of worn-out components and failed apparatus.

There is essentially one type of overhaul — major — in the present operational practice of repair enterprises. However, it should be noted that repair enterprises also perform a large volume of work on aircraft maintenance according to Form No. 5 every 3,000-3,600 hours of accrued flight time. This form of maintenance also includes overhaul operations for some types of aircraft.

The following combination of operations is usually carried out during major overhaul of an aircraft:

- all supporting elements of the airframe structure are completely disassembled, carefully inspected and checked for flaws in order to ensure the operational safety of the aircraft during the next overhaul cycle;

- all elements and components of the airframe structure, having flaws or requiring modification according to results of tests under repeated loads and the recommendations of the chief designer, are restored, replaced or strengthened;
- a detailed inspection for flaws is carried out, and the aircraft systems (hydraulic, fuel, air, water, and electrical) are restored or replaced, including the wiring and cable ducts;
- the apparatus and special equipment are repaired or replaced;
- the heat and sound installation of the fuselage, passenger seats and other everyday equipment are repaired or replaced;
- the decorative and anticorrosion trim of the aircraft is restored inside and outside. /58

It is well known that major overhaul of an aircraft is feasible only when the majority of the main apparatus and supporting elements of the airframe structure require this overhaul based on their technical condition, especially the fuselage, tail assembly, etc. On the other hand, development and introduction of new and more progressive procedures for overhaul, which provide for greater differentiation of the repair operations according to the hours of accrued flight time, are required in order to avoid high expenditures of resources and time to carry out major overhauls.

An identical period of aircraft operation is arbitrarily used for each of the possible overhaul procedures (Figure 25).

It follows from Figure 25 that there is constantly increasing differentiation of the repair operations as a function of the total hours of accrued flight time by the aircraft as the number of the procedures increases. And, finally, in procedure IV,

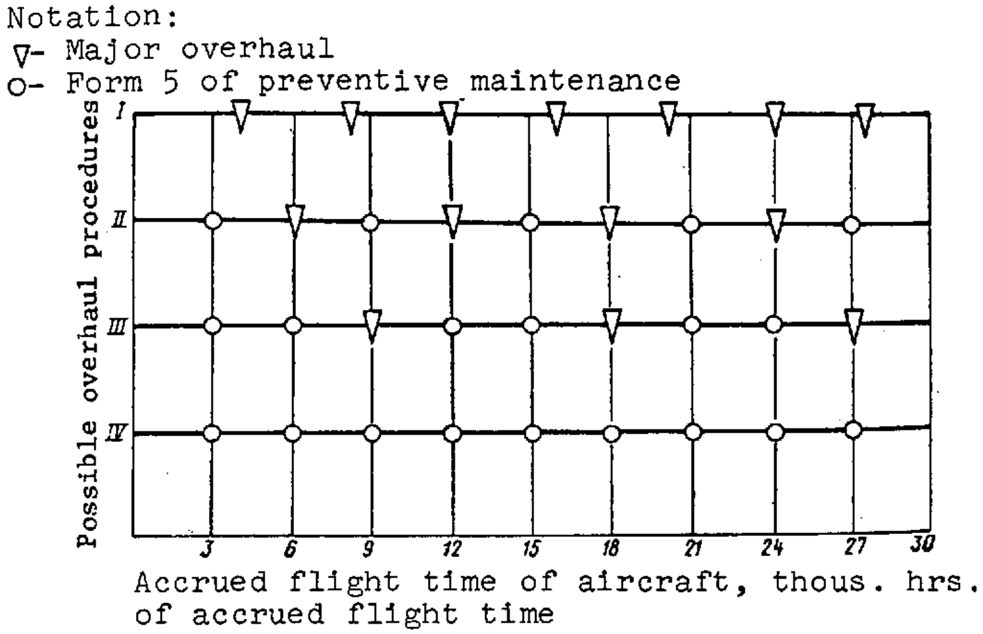


Figure 25. Possible procedures for overhaul of transport aircraft.

major overhaul does not exist in the usual understanding of this word, and the entire required volume of repair operations is performed in individual stages simultaneously with the periodic forms of preventive maintenance of the aircraft, for example, with form No. 5.

A study of procedures I and II showed that aircraft delivered to the plants for major overhaul after completing the established repair cycle are in a different technical condition. The repair cycles of aircraft are determined essentially by the service life of the individual replaceable parts and apparatus, timely overhaul or replacement of which during preventive maintenance makes it possible to extend the operation of the aircraft without major overhaul, rather than by the operating life of the individual replaceable parts and apparatus. As a result, many of the operations are performed prematurely on aircraft which are delivered for major overhaul based on the previously established deadline. It is quite natural that a significant portion of the labor and resources for materials and spare parts is expended in this case on disassembly and assembly operations and correction of failures and malfunctions, which occurred during disassembly. The technical capabilities, included in the design of the main supporting elements of the aircraft, are not fully utilized.

The method of performing major overhaul of a modern transport aircraft during a single process (procedures I and II) is obsolete in most cases. In this method, the aircraft is taken out of operation for a prolonged period. The volume of operations carried out in overhauling the average mainline aircraft is approximately 35,000-40,000 man-hours.

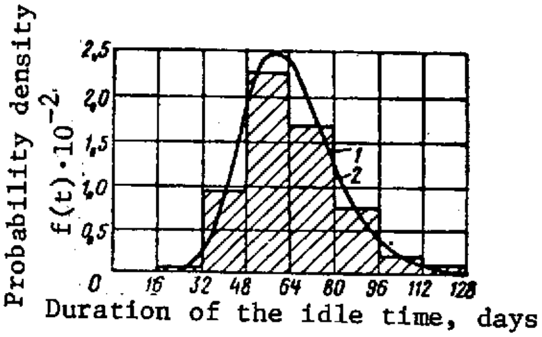


Figure 26. Example of distribution of the idle times of Il-18 aircraft during major overhaul:

1 - Experimental data; 2 - Theoretical distribution curve.

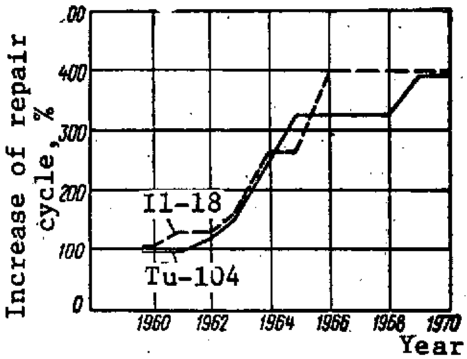


Figure 27. Increase of the repair cycle of Tu-104 and Il-18 aircraft (1960 data are taken as 100%).

As can be seen from Figure 26, the distribution of the empirical data on the length of idle times of the Il-18 aircraft during overhaul is approximated by logarithmically normal law. The large spread in the length of idle times of the aircraft is explained by the different volumes of operations performed during overhaul due mainly to modifications and reequipping of individual systems.

As experience is accumulated in operation and repair, the repair cycles of the aircraft usually increase (Figure 27). However, when using repair procedures I and II (see Figure 25), the rates of increase of the repair cycles remain high, but the increase itself has considerable limitations. This does not occur if /60 repair procedure IV is used, in which any apparatus and assembly which has exhausted its operating life, may be easily replaced during the routine periodic form of maintenance of the aircraft at the ATB.

A similar repair procedure is employed by certain foreign airline companies. The most widely used are the block and continuous repair methods [26].

With these methods, the main elements of the aircraft structure are not restored simultaneously, but differentially, strictly according to the completion of the operating life. In other words, overhaul is carried out in stages throughout the repair cycle established for the aircraft.

Development of repair methods is begun by a company from the early stages of developing the aircraft and is then outlined in the official technical documents delivered to the airline companies together with the aircraft, in particular in the Preventive Maintenance Manual and the Manual On Organization of Overhaul.

In the block method, all necessary repair operations are carried out in sequence according to specific blocks (groups) of aircraft zones during performance of periodic forms of maintenance on it.

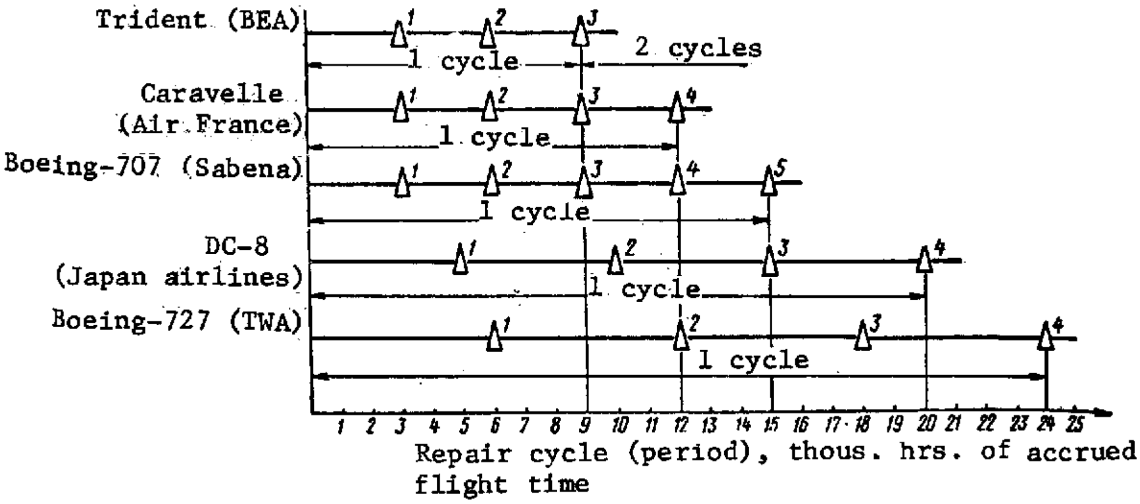


Figure 28. Diagram of constructing a system of block repair of certain types of passenger aircraft:

1, 2, 3, 4, 5 — maintenance with simultaneous completion of part of the repair operations and modification of the structure.

Four or five or more stages of repair are performed at intervals of every 3,000-6,000 hours of accrued flight time during the repair cycle (9,000-15,000 hours of accrued flight time or more) in the block method of aircraft repair. A diagram of repairing certain types of aircraft in individual large airline companies of different countries is presented in Figure 28. It /61 follows from the given diagram that the repair of the Trident aircraft is carried out in three stages, that of the Caravelle — in four stages; and that of the Boeing-707 — in five stages, while observing the intervals of 3,000 hours of accrued flight time between the repair periods. The intervals between the repair periods for the DC-8 and Boeing-727 aircraft have increased considerably — to 5,000 and 6,000 of accrued flight time, respectively. The second cycle begins upon completion of one repair cycle, etc.

The major structural assemblies are inspected carefully during operation, using ultrasonic and roentgenoscopic methods in certain zones. The following inspection graph is recommended for all the BAC-111 aircraft within the limits of a repair cycle equal to 24,000 hours of accrued flight time or 32,000 landings (Table 12).

TABLE 12.

Frequency of inspection, hrs. of accrued flight time (landings), thous.	Volume of selecting aircraft for inspection
Main structure	
7.5(10)	10% of fleet
12.0(16)	40% "
24.0(32)	100% "
Tail portion and power plant support assemblies	
3.0(4.0)	10% of fleet
4.5(6.0)	20% "
6.0(8.0)	100% "

It should be noted that the block method of repair is used primarily for all the main types of aircraft in many countries. Lists of the operations which should be performed during overhaul of a certain block of zones are compiled by the company as a function of the operating lifetime of the assemblies, components and apparatus, and also to avoid simultaneous operations, which cause a large number of personnel to concentrate in individual zones of the aircraft. Some data on the length and structure of the repair cycle of aircraft of foreign airline companies are given in Table 13 [37].

The aircraft is removed from flights for 2-3 weeks, primarily during the spring and winter seasons, to perform each of the repair stages which must coincide with the periodic forms of maintenance. The labor expenditure in this case comprises 10,000-15,000 man-hours (including labor expenditures for maintenance and modification).

C - [illegible]

TABLE 13.

Type of aircraft	Repair cycle, hrs. of accrued flight time	Number of repair stages per cycle	Accrued flight time between individual repair stages, hr.
	Eastern Airlines (USA)		
DC-8	24 000	4	6000
DC-9	28 000	4	7000
Boeing-720	24 000	4	6000
Boeing-727	24 000	4	6000
	Trans World Airlines (USA)		
Boeing-707	28 000	4	7000
Boeing-727	24 000	4	6000
Convair-880	21 000	3	7000
DC-9	14 000	4	3500
	National Airlines (USA)		
DC-8	36 000	6	6000
Boeing-727	24 000	4	6000
	Air Canada		
DC-8	18 000	3	6000
DC-9	18 000	3	6000
Vanguard	13 500	3	4500
Viscount	18 000	5	3600
	Alitalia (Italy)		
DC-8	24 000	4	6000
Caravelle	15 000	3	5000
Viscount	15 000	3	5000
	Swissair (Switzerland)		
Convair-990	18 000	3	6000
DC-8	13 500	3	4500
Caravelle	12 000	3	4000
	Japan Airlines		
DC-8	20 000	4	5000
Convair-880	20 000	4	5000
Boeing-727	24 000	4	6000

The schedule for performing maintenance of aircraft (Figure 29) in the Italian airline company, Alitalia, according to regulations DC and E, including specific repair stages, shows that not one of the aircraft is sent to the shops for performance of labor expenditure regulations CS and E during the summer months from May through September due to the increase in the traffic volume.

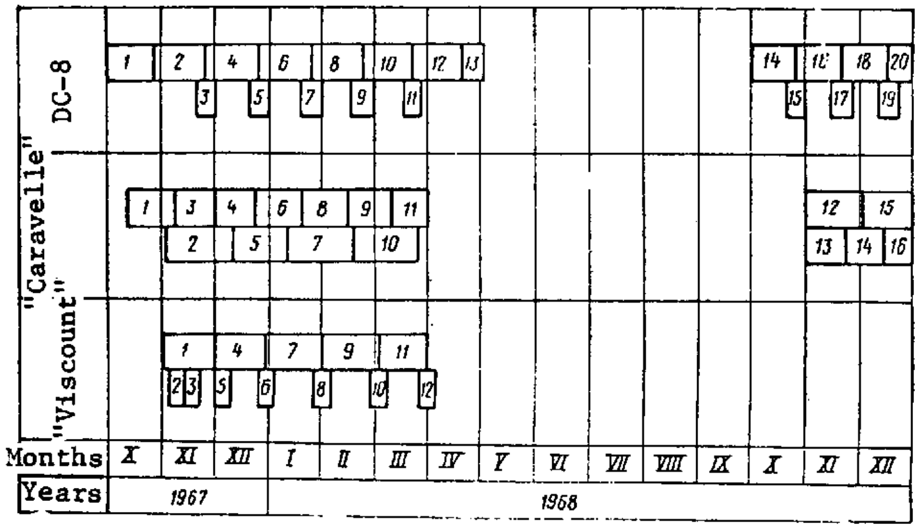


Figure 29. Schedule for performing periodic types of maintenance of the DC-8, Caravelle and Viscount aircraft (the routine numbers of delivery to the shops are indicated for each type of aircraft).

There are several versions of constructing a system of block repair of aircraft in the operation of the airline companies. Some of them, used for the Caravelle aircraft, are presented in Figure 30. /6

The cross-hatched columns arbitrarily indicate: 1- the volume of operations carried out every 1,500 hours of accrued flight time; 2, 3, 4 - additional operations carried out every 3,000, 6,000 and 12,000 hours of accrued flight time, respectively. It is obvious from the figure that each succeeding variant of the

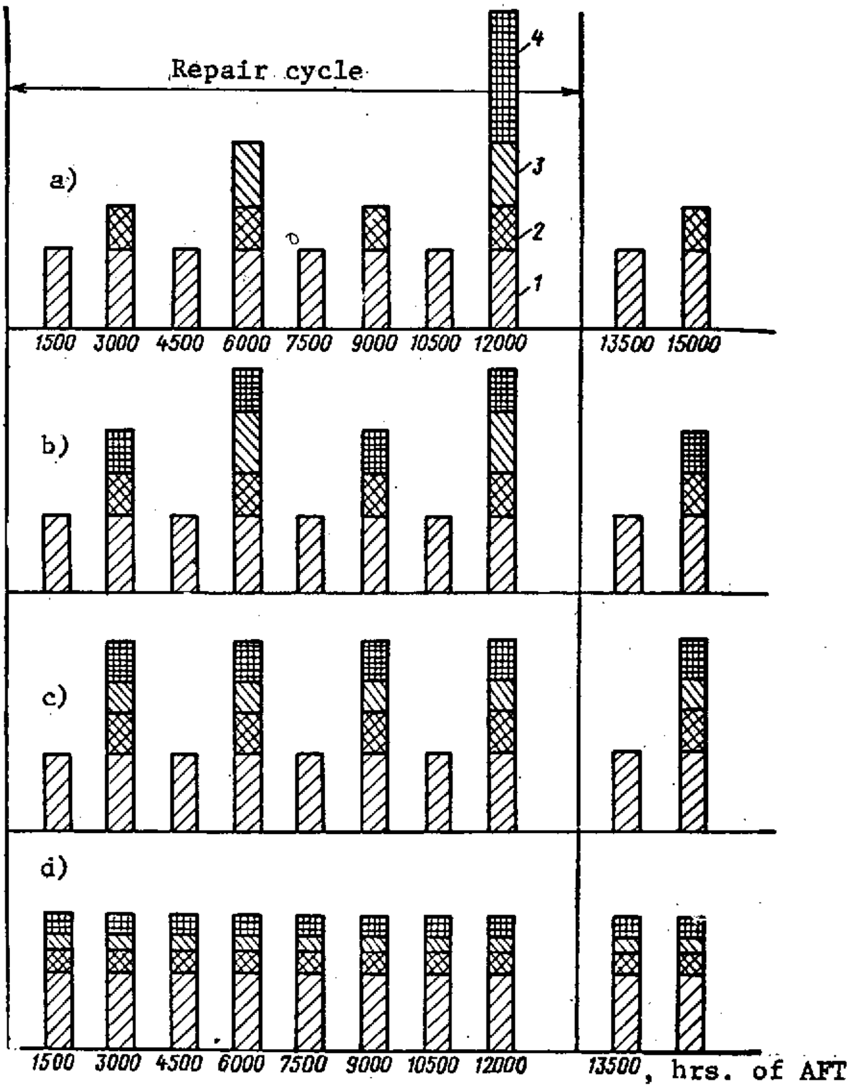


Figure 30. Some varieties of constructing a block repair system:

a- Usual distribution of operations carried out on the aircraft during the repair cycle; b- 12,000-hour operations are distributed between maintenance cycles, carried out every 3,000 hours of accrued flight time; c- 12,000 and 6,000-hour operations are distributed between 3,000-hour maintenance cycles; d- 12,000, 6,000 and 3,000-hour operations are uniformly distributed between maintenance cycles performed every 1,500 hours of accrued flight time (AFT).

repair organization differs from the preceding one by a more uniform distribution of repair operations between the periodic forms of maintenance. In the fourth variant, for example, total uniformity is achieved in the volume of operations on maintenance and repair, which is carried out every 1,500 hours of accrued flight time.

The continuous repair method — a further development of the block method — has become used more and more widely recently in many airline companies which have a relatively small fleet of aircraft of the same type (from 3 to 10 aircraft). With this method, the structural elements of the aircraft are restored not only during periodic maintenance (every 3,000-6,000 hours of accrued flight time or more), but also when performing less labor-consuming operations (for example, every 200-300 hours of accrued flight time).

With this method of repair, the aircraft is never in the repair shop for more than 8-10 hours up to 3,000 or 6,000 hours of accrued flight time (depending on the repair variant used). Only when fulfilling the maintenance regulations for 3,000 or /6 6,000 hours of accrued flight time, including such operations as repair of the everyday equipment and restoration of the paint, is the aircraft taken off flights for a period up to 5 days. The given repair method is used by some American airline companies on small groups of Electra, DC-8 and other aircraft; it may also be used on the English Trident, VC-10 and BAC-111 aircraft.

The main advantages of the continuous repair method are that investigation of the technical state of individual elements of the aircraft during the established repair cycle is improved; the technical utilization factor of the aircraft is increased; peak loads of the repair shops are reduced due to uniform distribution of operations of maintenance and repair throughout the year.

The disadvantages of this method include the complexity of scheduling and calculating the operations.

The fact that each aircraft newly entered into operation has higher initial intervals between the repair stages compared to the preceding types is typical for foreign firms and airline companies (Table 14).

TABLE 14.

Type of aircraft	Year of entering service	Initial intervals between repair stages, hrs. of AFT
DC-6	1947	700
Convair-340	1952	1,000
DC-7	1954	2,000
DC-8	1959	2,500
Boeing-727	1964	3,000
VC-10	1964	3,000
Boeing-737	1967	4,500
Boeing-747	1970	9,000

The intervals between repair stages are improved during operations. It is clearly obvious from the data presented in Figure 31 that the rates of increase of the intervals for the Boeing-727 aircraft, which entered service in 1964, are much higher than those for the DC-8 aircraft, which has been in operation since 1959.

4. Methods of Optimizing Maintenance Conditions

A large number of papers of Soviet and foreign authors have been published up to the present on problems dealing with selecting the optimum procedures and modes of maintenance. The first papers on this topic began to appear at the beginning of the 1950's. In the bibliography of [44], published in 1965, 88 titles /66 are indicated, and several hundred articles are contained in survey [2], which also includes articles of Soviet authors.

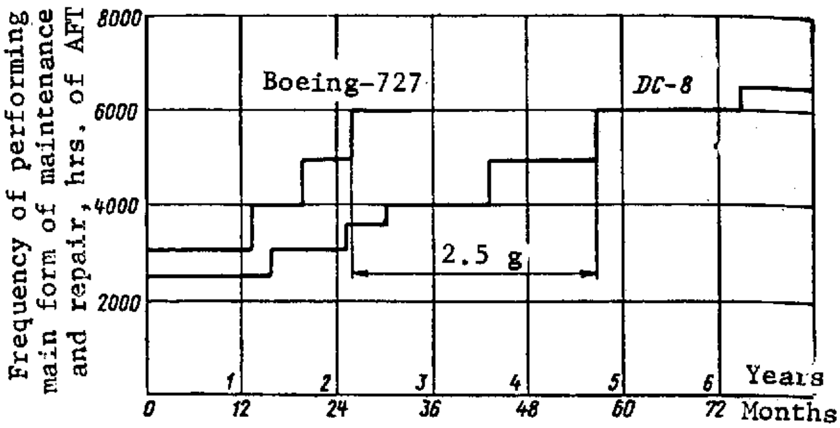


Figure 31. Variation in frequency of performing repair on DC-8 and Boeing-727 aircraft.

When selecting the optimum conditions for aircraft maintenance, two groups of problems arise:

- determination of the optimum maintenance frequency for individual apparatus, blocks and assemblies;
- grouping of maintenance operations on individual apparatus and assemblies into optimum forms of the maintenance regulations for the aircraft as a whole.

It follows from sources in the literature and investigations carried out by different organizations that the problems of the first group are more easily resolved; the proper attention is not yet being devoted to solution of the problems of selecting the optimum modes of maintenance for the aircraft as a whole.

When determining the optimum frequency of maintenance for individual apparatus, units and assemblies of aircraft, different criteria are taken as the optimum. In particular, the optimum criterion is esbablished from the condition of achieving the required reliability of the apparatus during the maintenance period $P(t)_{m.p}$ with minimum labor expenditure $T_{T.O}$ to perform maintenance operations T_p and to eliminate failures T_y. The optimum frequency of maintenance for individual apparatus x_{opt} is determined in this case from the condition of achieving the maximum value of the ratio:*

$$P=\max\{\frac{P(t)_{m.p}}{T_{T.O}}\}.$$

In a number of cases the maximum value of this ratio may be calculated by imposing the appropriate limitations, for example, the minimum labor expenditure at a given level of reliability $P(t)_{m.p}=P(t)_d$, and $T_{T.O}=\min$ or the maximum reliability at a given level of labor expenditure $P(t)_{m.p}=\max$, and $T_{T.O}=T_d$. /67

The expanded expression for P has the following form:

$$P=\frac{e^{-\omega\eta x}}{T_y\omega\eta x+T_p\frac{\tau_p}{x}}, \tag{6}$$

where ω is the failure rate of the apparatus; η is the frequency of failures during the maintenance cycle. The ratio of the number of failures during the maintenance cycle to the total number of failures corrected during the operational period of the aircraft is calculated; x is the frequency of maintenance, varied as a continuous value within the range of the possible minimum and maximum values; T_y is the labor expenditure to correct sudden failures during the maintenance cycle; T_p is the labor expenditure to perform preventive maintenance; and τ_p is the actual frequency of apparatus maintenance (up to optimization).

*The method was proposed by V.V. Lysov.

The dependence of η on x has the form:

$$\eta_i = 1 - e^{-\alpha_i x_i}.$$

Coefficient $\alpha_i = \frac{\ln\frac{1}{1-\eta_i}}{\tau_{pi}}$ is calculated for each i-th assembly or apparatus, on the basis of the values of η_i achieved at an existing frequency of τ_{pi}.

For practical calculations, the value of x of interest and the corresponding value of P_{max} are obtained by constructing a graph of P=f(x) within the appropriate range of variation of x. The variation of parameters $P(t)_{m.p}$, $T_{T.O}$ and P as a function of x for one of the components is shown in Figure 32 as an example with the following arbitrary initial data:

Parameter	α	ω, 1/hr	τ_p, hr	T_y, MH*	T_p, MH	$T_{T.O}$, MH
Value of the parameter. . . .	0.07	$1 \cdot 10^{-3}$	100	5	10	10.45

*MH = man-hours.

The results of the calculations performed according to formula (6) are presented below:

x, hrs	10	100	400	1,000
$P(t)_{m.p}$	0.995	0.910	0.670	0.368
$T_{T.O}$ during period x, man-hrs.	100.03	10.45	4.50	6.00
P	0.0099	0.0870	0.1500	0.0613

The derivative of P must be taken modulo x and it must be set equal to zero in the general case for calculating the maximum of expression (6). /68

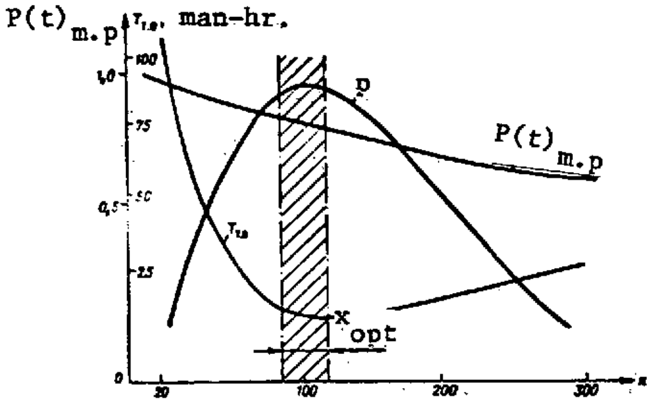


Figure 32. Nature of variation of parameters $P(t)_{m.p}$, $T_{T.O}$ and P as a function of x.

There is also a method of optimizing the periods of performing maintenance based on the development of failures by the apparatus [29].

With this method, the probability of a joint event — development of a malfunction and no-failure $P_{n.\bar{o}}(t)$ — is maximized with optimum periods of performing maintenance.

It is assumed that development of failures will be prevented as malfunctions are corrected during the established periods.

The development of failure of an apparatus, when a malfunction occurs in its operation, may be represented in the following manner. The malfunction, which appears at a random moment of time t_1, begins to develop at the beginning of operation t=0. The second stage of development of the failure, which continues for random time t_2, begins from this moment of time. Failure of the element occurs at the moment of time $t_{OT}-t_1+t_2$.

When the malfunction precedes failure, there is a probabilistic or functional dependence between the values of the time of occurrence of the malfunctions and failures.

The probability of a malfunction occurring during a small time segment $(t, t+dt)$, preceding the beginning of maintenance, is equal to $f_1(t)dt$.

The probability that failure will not occur in a technical device from moment of time t to the beginning of maintenance t_o is equal to

$$1-F_2(t_o-t),$$

where $F_2(t_o-t)$ is the probability of a failure occurring within time (t_o-t).

In this case, an element of probability $dP_{n.\bar{o}}(t)$ is equal to the product of the considered probabilities: /69

$$dP_{n.\bar{o}}(t)=[1-F_2(t_o-t)]\,f_1(t)\,dt.$$

Carrying out summation over all values of t from 0 to t_o, we obtain

$$P_{n.\bar{o}}(t_o)=\int_0^{t_o}[1-F_2(t_o-t)]\,f_1(t)\,dt. \qquad (7)$$

It is recommended that the periods of performing maintenance be optimized on the condition that the times of malfunctions t_1 and failures t_2 be distributed according to an exponential rule. The use of other types of distribution rules, including normal and uniform density, essentially have no effect on the final result (the difference in the maintenance periods may be 10-15%).

Expression (7) for the exponential rule of the time distribution of malfunctions and failures has the form:

$$P_{n.\bar{o}}(t_o)=\int_0^{t_o}e^{-\omega_2(t_o-t)}\omega_1 e^{-\omega_1 t}\,dt.$$

The optimum period of apparatus maintenance is calculated in the general case as the smallest positive root of the equation

$$\frac{dP_{n.\bar{o}}(t_o)}{dt_o}=0.$$

However, in practice the optimum value of t_o is found from the graph of $P_{n.\bar{o}}(t_o)=f(t)$ within the time range t of interest (Figure 33).

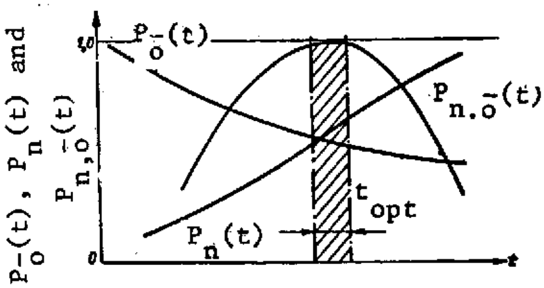


Figure 33. Nature of variation of parameters $P_{\bar{o}}(t)$, $P_n(t)$ and $P_{n.\bar{o}}(t)$ as a function t.

Besides the foregoing, there are other methods of optimizing the periods of performing maintenance of apparatus [1, 32, 33]. By using any of them, periods of maintenance of a number of apparatus and assemblies, which do not coincide, are obtained. /70 Implementation of the results obtained would require continuous maintenance. Therefore, even with known periods of maintenance of each of the elements, the problem of selecting the optimum frequency of maintenance of the machine as a whole remains unsolved.

Let us consider one of the methods of solving the given problem [27].

Let us assume that all operations on maintenance (set M) may be divided into two groups. The first group (subset M_1) includes the timely performance on which the reliability and safety of flights depend. The second group (subset M_2) includes operations, which have no direct effect of flight safety when their periods of performance are changed.

The prescribed (maximum permissible) frequency of performing $x_{1;i}$ ($x_{1;1}<x_{1;2}<\ldots<x_{1;n}$), obtained by one of the methods outlined above, and direct expenditures $y_{1;i}$ are known for each i_1-th operation of the first group. The combination of operations of the first group is depicted schematically in Figure 34.

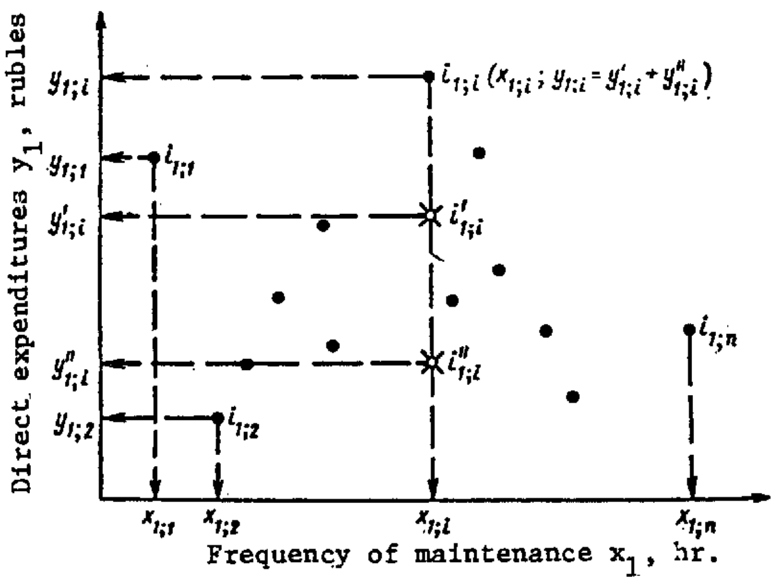


Figure 34. Combination of maintenance regulation operations of subset M_1.

The determined functional dependence of specific expenditures for maintenance and repair $y_{2;i}$ on the frequency of maintenance $x_{2;i}$:$y_{2;i}=f(x_{2;i})$ should be known for each i_2=i-th operation of the second group. The optimum frequencies of performing the individual operations are denoted in Figure 35 by the points $x_{2;i}$($x_{2;1}<x_{2;2}<\ldots<x_{2;n}$), in which the first derivatives of the function $f'(x_{2;i})=0$.

Moreover, let us assume that the average annual accrued flight time of the aircraft W_{aft}, the hourly losses due to idle time y_p and the average idle times during performance of each i-th operation B_i are known. /71

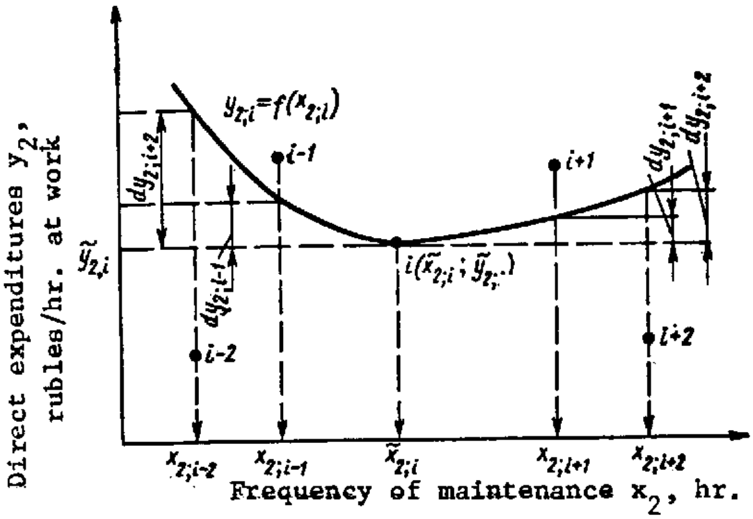


Figure 35. The combination of maintenance regulation operations of subset M_2.

Under such conditions the annual expenditures for maintenance and repair of any machine, taking into account losses due to idle times, comprise Y rubles:

$$Y=\sum_{\substack{i=1\\ i\in M_1}}^{n_1}\left(\frac{W\text{aft}}{x_{1;i}}-1\right)+\sum_{\substack{i=1\\ i\in M_2}}^{n_2} y_{2;i}W_{\text{aft}}+y_p\sum_{\substack{i=1\\ i\in M}}^{n} B_i\left(\frac{W\text{aft}}{x_{1;i}}-1\right). \tag{8}$$

The problem is in selecting a set of values x_i* (i=1, 2, 3, ...), at which functional (8) is minimized.

An attempt is usually made to perform the maximum possible number of operations to coincide in time in order to reduce losses due to idle times of the machine. In such cases, the period of performing each i-th operation should be a multiple of the period of performing (i-1)-th operation, i.e.,

$$x_1^*=\frac{1}{q_1}x_2^*=\frac{1}{q_2}x_3^*=\cdots=\frac{1}{q_{n-1}}x_n^*, \tag{9}$$

where $q_1<q_2<\ldots<q_{n-1}$ are numbers of a natural series.

The combination of numbers x_i^*, which satisfy condition (9), may be called an <u>improper lattice</u>, because it has gaps in the space of the type $x_i = \beta x_{min} (\beta = 1, 2, 3, \ldots)$.

The values of x_n^* and x_1^* are usually known beforehand. They are selected on the basis of tactical concepts. The number of intermediate forms of maintenance and the frequency of performing /72
them may be calculated as a result of the canonical expansion of the quotient:

$$\frac{x_n^*}{x_1^*} = \nu_1^{\alpha_1} \nu_2^{\alpha_2} \ldots \nu_k^{\alpha_k}.$$

Having the canonical expansion of this quotient, we may obtain as many improper lattices of type (9) as we can make transpositions from the exponents of the canonical expansion:

$$N = \frac{\left(\sum_{i=1}^{k} \alpha_i\right)!}{\alpha_1! \, \alpha_2! \ldots \alpha_k!}.$$

The sum of the exponents of canonical expansion $\sum_{i=1}^{\kappa} \alpha_i$ denotes the maximum possible number of forms of maintenance in a single cycle, without counting the first form x_1^*. The values of $q_1, q_2, \ldots, q_{n-1}$ for each of the improper lattices are calculated by sequential multiplication of the bases of the canonical expansion.

<u>Example</u>. Let $x_n^* = 3{,}000$ hrs. and $x_1^* = 20$ hrs. Canonical expansion of the quotient will then have the form $\frac{3000}{20} = 150 = 2 \cdot 3 \cdot 5 \cdot 5 = 2 \cdot 3 \cdot 5^2$. The maximum possible number of forms of maintenance in the given case will be equal to 5, and the number of possible improper lattices of type (9) is $N = \frac{4!}{1! \cdot 1! \cdot 2!} = 12$.

The values of q_i are presented as a function of the number of the lattice in Table 15.

TABLE 15.

Number of lattice	q_1	q_2	q_3	q_4
1	2	10	30	150
2	2	6	30	150
3	2	10	50	150
4	3	6	30	150
5	3	15	30	150
6	3	15	75	150
7	5	15	75	150
8	5	10	50	150
9	5	10	30	150
10	5	15	30	150
11	5	25	50	150
12	5	25	75	150

The corresponding frequency of performing the forms of maintenance is calculated by multiplication of x_1^* by the values of q_i. Thus, the frequency of performing the forms of maintenance for the first lattice in hours of accrued flight time will have the following form: 20 — 40 — 200 — 600 — 3,000.

After reducing all operations to the corresponding forms of maintenance, it is natural to find the global minimum of functional (8) for the set of all possible lattice spaces of type (9).

Since the operations in the first group may be combined only /73
with the preceding operations, the optimum combination for them should be expressed by the condition

$$S'(n) = \min_{1<l<n_1} \left\{ y_{1;\,l} \left[\left(\frac{W_{aft}}{x_{1;\,l-1}} - 1 \right) - \left(\frac{W_{att}}{x_{1;\,l}} - 1 \right) \right] \right\}. \qquad (10)$$

A combination of the following type may be used for operations of the second group:

$$S''(h)=\min_{1<i<n_2}\begin{Bmatrix} W_{aft}\,[f(x_{2;\,i-1})-f(x_{2;\,i})] \\ W_{aft}\,[f(x_{2;\,i+1})-f(x_{2;\,i})]\end{Bmatrix}. \qquad (11)$$

Procedures (10) and (11) make it possible to perform sequential reduction of the number of operations, using an electronic computer, so that the least expenditures for maintenance and repair are obtained with any fixed number of points x_i*.

5. Some Trends in Development of a Maintenance and Repair System

Consideration of a preventive maintenance and repair system will be incomplete if the new trends in this development are not indicated which have recently appeared and which have a considerable effect on the requirements and indices of aircraft maintability.

The first to which attention should be given is development and more extensive use of the method of replacement and repair of aircraft apparatus and finished components according to the actual technical state, instead of replacement and repair strictly according to the established repair cycles.

Actually, the repair cycle for apparatus, components and assemblies, subject to wear and aging during operation, is the value t_p, which under the normal law of the time distribution density of no-failure operation f(t) is 3σ times less than the average time of the mean-cycles-between-failures t_{cp} in the best case (Figure 36).

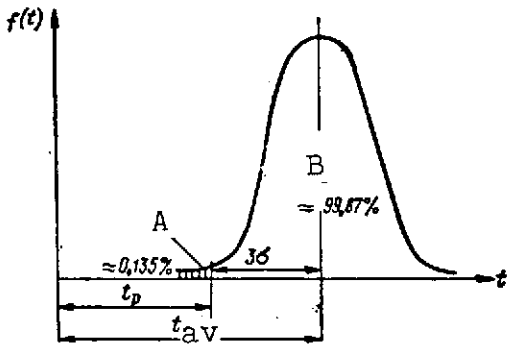


Figure 36. Distribution of the repair cycle of an apparatus: t- operating time; σ- mean square deviation; A- percentage of failures within the range t_p; B- premature replacement.

Hence, it follows that replacements of apparatus will be performed prior to their failure in the overwhelming majority of cases (99.865%), and failures of the apparatus and their replacement ahead of schedule will occur in 0.135% of the cases. In other words, strict observation of the established repair cycle for all apparatus without exception, regardless of the actual technical state of each of them, does not eliminate failures and, what is most important, leads to premature replacement of the greater portion of apparatus and components of an aircraft.

For those components which are not subject to wear and aging during operation (this refers primarily to certain components of electronic equipment), the failure rate is a constant value throughout the entire period of oepration. This indicates /74 that a single operating lifetime until repair cannot generally be established for such components.

Investigations, carried out by the American airline company United Airlines according to Federal Aviation Agency Circular No. 120-17, dated 31 December 1964, are of specific interest, out of the materials available on this problem [49]. The airline company and the manufacturing firms developed and are implementing special programs of maintenance and repair of electronic and electrical equipment, and of the hydraulic, fuel and high-altitude systems for the DC-8, Boeing-720, Boeing-727 and Boeing-737 aircraft. The purpose of these programs is to study the relationship between the operating lifetimes and the reliability of the aircraft.

An overhaul program as a function of reliability (RCOP — Reliability Controlled Overhaul Program) is used for the electronic equipment. The failure rate for this group of apparatus, as is known, is a constant value. The United Airlines Company did not find a single case when the electronic equipment failed because of wear or aging.

A Component Reliability Program (CRP) is used for the auxiliary apparatus of the electrical equipment. According to this program, the apparatus is serviced which has high repair costs, a low time-variable failure rate, and the necessary control and checking equipment for checking technical condition during operation.

A program of replacement and repair according to the results of checking (TARAN — Test And Replace As Necessary) is used for the hydraulic, fuel and high-altitude systems. With this program, instead of replacing the repairing the apparatus upon completion of the established operating lifetime, they are checked on the aircraft without disassembly in order to determine their actual technical condition. If no deviations from the norm are detected during the check, the apparatus is not replaced. /75

The Turbine Engine Reliability Program (TERP) is used for the components of gas turbine engines.

The data which characterize the extent of using the method of replacement and repair of assemblies according to its actual condition on several types of aircraft of an airline company for the end of 1969 are presented in Table 16. It is obvious from Table 16 that more than 60% of the apparatus for all types of aircraft is replaced according to the actual technical condition.

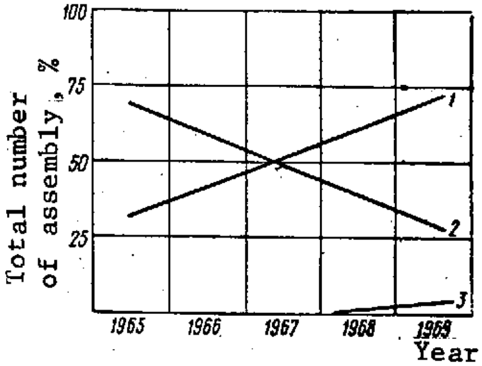


Figure 37. Variation of the total number of Trident aircraft assemblies, replaced according to the technical condition:

1- replaced according to technical conditions; 2- replaced according to completion of operating lifetime; 3- checked in laboratories.

The method of replacing assemblies according to their actual technical condition is widely employed on the English (VC-10, BAC-111 and Trident aircraft. Figure 37 shows how the number of items, replaced and repaired according to their actual technical condition, on the Trident aircraft in the English airline company BEA has been increasing from year to year. By the end of 1969 the number of items, replaced based on their condition, reached 72%. The condition of 66% of the items is determined directly on the aircraft, and only that for 6% — in the laboratories.

The distribution of the repair cycle operating life for 900 different items on the BAC-111 aircraft according to data for 1965 and 1969 is presented below.

TABLE 16.

Type of aircraft	Total no. of items replaced	of those replaced		Share of items replaced based on condition, %
		according to operating life	according to condition	
DC-8	528	167	361	68
Boeing-720	456	168	288	63
Boeing-727	460	144	316	70
Boeing-737	367	134	233	63

It follows from the given data that the overwhelming majority of aircraft equipment is replaced based on the actual technical condition.

/7

Repair cycle operating life, hrs. of accrued flight time	Less than 3000	From 3000-5000	From 5000-10000	More than 10000	Not established (replacement based on actual technical condition)
		1965			
No. of items, %	1.0	1.25	7.5	18.45	71.8
		1969			
	—	0.5	6.6	10.8	82.1

The method of replacement of equipment and components according to their actual technical condition is progressive. Its introduction is based primarily on extensive knowledge of the reliability of the equipment and structural elements, the use of objective means of checking their technical condition during operation, and also on a high level of maintainability (ease of checking, free access to the apparatus and equipment, their ease of disassembly and interchangeability).

The second problem deserving of attention is development and extensive introduction of methods of aircraft maintenance and the individual components so as not to exceed the established intervals. Only a maximum frequency of performing the maintenance operation has been established by the development firm for each component according to this principle. Any airline company, on the basis of their own working conditions and capabilities, by using this principle, may easily develop the necessary procedures for maintenance and repair, which provide the least idle times of the aircraft and expenditures of resources.

The principle of not exceeding the established intervals for performing maintenance operations is more flexible than that of strict designation of a base frequency with limits, regardless of the operating conditions of aircraft and the capabilities of the operational enterprises. However, successive use of this principle is possible only when the appropriate values of the maintenance intervals are established for each individual item, finished component, and assembly of the aircraft structure.

Preventive maintenance so as not to exceed established intervals is widely employed at present on the English Trident, BAC-111 and VC-10 aircraft.

The assembly-apparatus method is becoming more and more widespread in aircraft repair. In this method of repair, separate operations of restoration of structural elements having a short operating life, as well as replacement of apparatus and assemblies, are carried out when the routine forms of maintenance are performed. The apparatus and assemblies removed from the aircraft under repair are removed from the aircraft and are sent to the warehouse to supplement the rotating stock. Some components, which require minor overhaul, are installed on the same aircraft from which they were removed.

The assembly-apparatus method of repair reduces the idle times of aircraft during repair and increases the operational readiness of aircraft. It contributes to an increase of the repair cycle of an aircraft, at the same time providing an adequately high reliability of equipment and systems. However, its introduction is possible only on aircraft which have a high level of structural maintainability. /77

A program of selective inspection and overhaul of structures is employed in a number of enterprises to further reduce the volume of repair operations, necessary on each aircraft after a specific number of hours of accrued flight time. With this program, the volume of repair operations, scheduled as a function of accrued flight time, is carried out only on specific parts in a strict sequence, rather than on each of the aircraft. The selection is established differentially for each zone of the aircraft as a function of susceptibility to failures, the frequency of repetition of failure and malfunctions, and the ease of access for inspection and overhaul.

A diagram of the organization of the program of selective extensive inspection and repair of the individual zones of the DV-8 aircraft at United Airlines is shown in Figure 38 [39]. Here, in particular, a 25-percent selection in repair of the removable parts of the wing and 50-percent selection in repair of the vertical stabilizer and rudder are provided. The nose /7 section of the fuselage is inspected and repaired on each of the aircraft (100-percent selection).

The selective extensive inspection and repair program appears in Table 17 for the entire aircraft.

It follows from these data that about 65% of all types of inspection and repair of the aircraft zones is performed with a

Notation: O- 25-percent; ◁- 50-percent; ▯- 100-percent

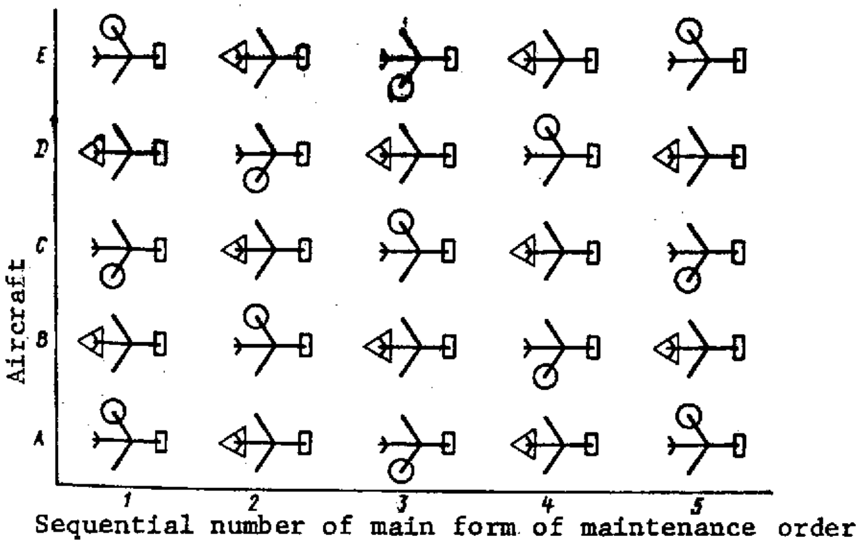


Figure 38. Diagram of organization of selective extensive inspection and repair of the structure of the DC-8 aircraft.

TABLE 17.

Indicator	Extent of selection, %					
	100	50	33	25	20	17
Number of types of inspection and repair according to aircraft zones	115	15	35	41	107	18
Percentage of total number of types of inspection and repair	34.5	4.5	10.5	12.5	32.5	5.5

selection of 50% or less. The given program is very flexible and makes it possible to obtain all the necessary information about the technical condition of the different zones of the aircraft in time with the least expenditures of time and resources.

In developing a maintenance and repair system for engines, we should note the following. Methods of replacement and repair of individual parts according to the actual technical condition have come into more extensive use in recent years due to the sharp increase in the cost of engines during operation. In this case, operations of replacement or repair of individual engine components are performed "on the wing" without removing the engines from the aircraft.

The data of the American airline company, Trans World Airlines, is of specific interest in this regard. This airline company began partial use of the method of engine overhaul "on the wing" in 1964. The number of repair operations, carried out "on the wing," has increased continuously from year to year. Thus, in 1964 there were 100 such operations, in 1965 — 132, in 1966 — 240, and in 1967 — 300 operations [40].

The time required for replacement of individual engine apparatus and assemblies directly "on the wing" of the Boeing-707 aircraft is usually much less than that for replacing the engine. Whereas an average of 10 hours is expended for replacement of the given type of engine, about 7 hours is required for replacement of the turbine disk, for example. This time has been reduced to 4-5 hours with the introduction of new tools.

The engine apparatus and assemblies, replaced or repaired "on the wing", may include: the combustion chambers, fuel flow regulators, the blades of some stages of the blower, compressor and turbine, high-temperature sections etc. There are special repair kits, which contain the necessary spare parts, instructions for replacement or repair, and a list of the required tools and /7
attachments, to perform the operations of repair or replacement of the individual apparatus and assemblies "on the wing."

As the assembly-apparatus method of engine repair "on the wing" has come into use, the number removed from the aircraft for shipment to the repair shop has been reduced considerably and the time the engines are in repair has been eliminated. In the final analysis, this makes it possible to considerably reduce the requirement of operational enterprises for spare engines (Figure 39) [35].

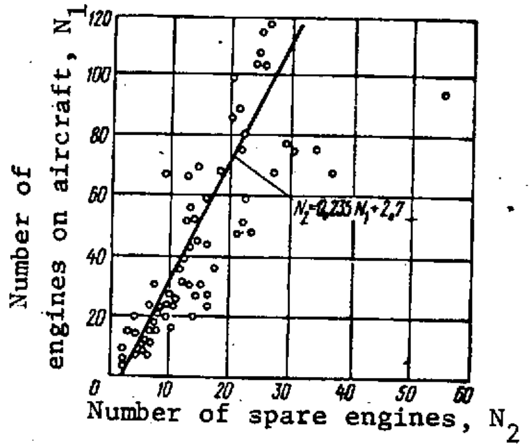


Figure 39. Dependence of the number of spare engines N_2 on the number of engines installed on aircraft N_1.

It follows from Figure 39 that there should be an average of about 30 spare engines for each 100 engines installed on aircraft in order to provide continuous operation of the aircraft fleet of the airline company, based on conditions in 1967. However, due to the use of new methods of repair in some airline companies, the number of spare engines was 1.5 times less than the indicated average values.

As the method of engine repair "on the wing" is introduced, the number of spare engines increases appreciably, which has a positive effect on the economic indices of the activity of operational enterprises.

The problem of implementing the method of engine repair "on the wing" in sufficient volumes deserves close attention. Its solution primarily requires an essentially new approach to engine design and manufacturing processes. It is necessary that an engine be suitable for the assembly-apparatus method of repair "on the wing" when a new type of engine is developed.

Such engines should be designed according to the model scheme and they should have a high level of maintainability.

In conclusion, the following should be noted. First, the materials outlined in this chapter undoubtedly do not reveal all aspects of the important and complex problem of maintenance and repair of aircraft. However, they are quite adequate with respect to the problems of providing maintainability of aircraft /8 structures. Secondly, successive introduction of new and more efficient methods of maintenance and repair during operation, which correspond more completely to time requirements, is senseless without solving problems of further improvement of aircraft and engine designs and their equipment to provide a high level of reliability and maintainability.

CHAPTER 3

MAIN CONCEPTS OF THE THEORY OF MAINTAINABILITY

1. Some Data from Renewal Theory

Theoretical investigation of the maintainability of complex systems and, in particular, of aircraft structures may be carried out by analyzing a sufficiently plausible mathematical model. The more natural model from this viewpoint may be the so-called renewal process, whose mathematical apparatus for study has been well developed. Certain aspects of renewal theory have become classical in this scheme and are of fundamental value.

One- and two-dimensional renewal processes [12], the meaning of which will be further explained, may be used successfully with respect to problems of maintainability. In this case, when speaking about a one-dimensional renewal process, we will have in mind a certain flow of clearly defined events (for example, the moments of the beginning or end of repair of a system) with positive time intervals x between events, distributed according to the same law.

Let us call these events renewal moments or regeneration moments, depending on circumstances, although following tradition, these events should be called failures. Interpretation of time, as will be seen directly, may be quite different. In particular, we can introduce the cost interpretation of continuous time.

The first generalization of the renewal process is achieved by introducing a two-dimensional process or a process with two states, each of which develops its own natural renewal process, and the relationship of the states is provided by the so-called imbedded Markov chain. This essentially means that the transition process to a new state does not depend on its pre-history.

The following generalization, which may also be used, is obtained by introduction of a multidimensional renewal process with a finite number of states and with a multidimensional imbedded Markov chain.

The presence of an imbedded chain and the non-negativity of segments in any case makes it possible to provide a very illustrative graphical analog of the mathematical model of multidimensional and in a special case, of two-dimensional renewal processes.

Further development of the mathematical model makes it possible to find the most diverse characteristics of maintainability. In particular, the function of maintainability and the function of losses are rather strictly defined, and limiting (stationary) ratios are found such as the average number of renewals within a given time and different types of coefficients.

When investigating maintainability, special attention is devoted to problems of correlation analysis, on the basis of which it is possible to evaluate the adaptability of the design of a complex machine to a given mode of maintenance, taking into account the reliability characteristics of its individual elements, apparatus and assemblies.

The Two-Dimensional Stochastic Process

Let us consider a two-dimensional stochastic process, defined in the space of two measurements s and z, in the following manner.

Let $x_1, x_2, \ldots, x_n$ be some random values, and let moments $x_1, x_1 + x_2, \ldots, x_1 + x_2 + \ldots + x_n$ form a flow of random events, such that the n-th event (an event of the first kind) occurs at moment

$$S_n = \sum_{i=1}^{n} x_i. \tag{12}$$

In this case we assume that the random values of x_1 are not positive and are distributed according to the same arbitrary law.

Further, let the new random value W_1 be related to each of the events of the first kind, and assume that N_s is a random number of events of the first kind, occurring at moment s, i.e.,

$$Z_s = \begin{cases} \sum_{i=1}^{N_s} W_i, & \text{where } N_s = 1, 2, \ldots \\ 0, & \text{where } N_s = 0. \end{cases} \tag{13}$$

Moments Z_s form a flow of events of the second kind. /82

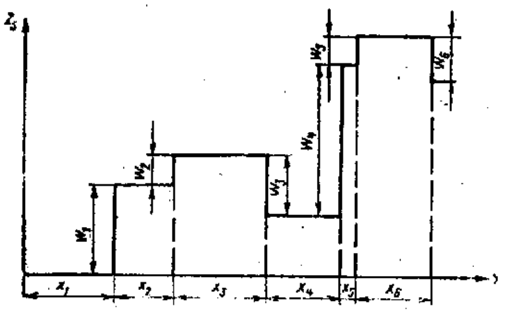


Figure 40. Model of a two-dimensional stochastic process {s, z}.

In renewal theory [12], stochastic process (12) has been named the renewal process, and stochastic process (13), related to it, has been named the accumulation process. The two-dimensional stochastic process {s, z} of interest to us is made up of (12) and (13) in coordinates s and z and leads to a very descriptive geometric interpretation (Figure 40).

Let us first consider the projection of a two-dimensional process $\{s, z\}$ onto axis s and let us determine the main characteristics of that projection which forms the renewal process (Figure 41):

1. The moment of renewal or the regeneration point is found from equation (12) and is calculated by the number n;

2. The length of time until n-th renewal is calculated from equation (12) as a random value s_n;

3. The number of renewals N_s during time interval s is found by fixing the interval (0, s) and calculating the number of n renewals, falling within this interval;

4. The renewal function is given by the mathematical expectation of random value N_s:

$$H_s = MN_s; \tag{14}$$

5. The parameter of the renewal process $\omega(s)$ is calculated by $\omega(s) = H'(s)$. Function $\omega(s)$ yields the number of renewals per unit time, if s is time.

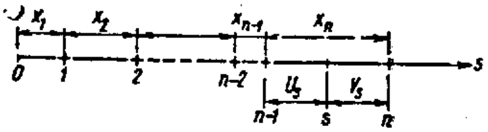


Figure 41. Determination of direct and reverse recurrence time.

Other characteristics of the renewal process are related to determining the law of distribution of that section x_n, on which point s falls. Let us consider interval [0, s) on the s axis and the last of sections x_n, which contains point s. We can talk about overlapping of point s by the interval of random length s_n. As indicated in probability theory [30], such overlapping has a unique property: the distribution of the value x_n with point s is distinct from the distribution of any other segment of x_n without this point. This is explained by the fact that the probability /83 of overlapping of point s, after it has been fixed, depends on the length of segment x_n. Actually, there is a greater probability of this point being overlapped by a segment of greater length, rather than vice versa;

6. The reverse recurrence time, or the jump-under, is calculated as a random value U_s of the length of the interval, calculated from fixed point x back to the (n-1)-th moment of renewal. If there were no renewals in interval [0, s), then $U_s=s$;

7. The direct recurrence time V_s, or the jump-over, is calculated from moment s to the n-th moment of renewal (see Figure 41). We note that always $U_s+V_s=x_n$, and this sum has the same distribution as any other random value of x_n;

8. The leading moments of value S_n or N_t, for example, dispersion, are found by the ordinary formulas of mathematical statistics.

The Multidimensional Stochastic Process

Let us now consider the projection of process {s, z} on the z-axis. Such a projection yields an accumulation process, and its characteristics are determined from equation (13) very similarly to the characteristics of the renewal process, if we assume that all values of W_i are essentially positive random values.

In this case, it is sufficient only to replace the term "renewal" with the term "accumulation."

Let us further consider a combination of mutually independent renewal processes $\{s_1, s_2, \ldots, s_i, \ldots, s_j, \ldots, s_n\}$, and let some process {Y} be formed by the elements of these processes and be developed by random transition from one renewal process to another.

Let us assume that the sequence of transitions in process {Y} forms a Markov chain, if the probability of transitions P_{ij} of process {Y} to state $\{S_j\}$ from stage $\{S_i\}$ does not depend on which states the process was in before it enters state $\{S_i\}$. After the process has entered state $\{S_j\}$, routine realization of the j-th renewal process is developed.

Thus, process {Y} is Markov only at specific "Markov moments" of time, to which transition from one renewal process to another is accomplished. For other moments of time, this process may not have Markov properties. This case determines the difference between {Y} and the Markov process, which is "imbedded" in process {Y}.

Thus, we regard process {Y} as a combination of an imbedded Markov chain and corresponding renewal processes. This process {Y} is called semi-Markov. Actually, we assume that the transition from $\{S_i\}$ to $\{S_j\}$ passes through time interval S_{ik} of random length, and k here denotes the number of elements of the /81
i-th renewal process, accumulated by the moment of transition to the j-th process.

The distribution function of segment S_{ik}

$$F_{ij}(s) = P\{S_{ik} < S/S_j\}$$

is calculated provided that the next transition will be carried out to state S_j.

If distribution functions $F_{ij}(s)$ for all values of i, j(i, j=1, 2, 3, ..., n) are exponential, the semi-Markov process {Y} is transformed to a Markov process. If n=1, a multidimensional semi-Markov process is transformed to a renewal process with a single state.

It is assumed that multidimensional process {Y} is given, if matrices $P=\|P_{ij}\|$ for the transition probabilities and $F=\|F_{ij}\|$ for the distribution functions are given.

When there is a large number of states, the graphical representation of process {Y} in the coordinate axes becomes inconvenient. In connection with this, let us denote one or another state simply by subscript i instead of $\{S_i\}$ and indicate transitions of system {Y} from state i to state j.

A very compact graphical interpretation of this process is now possible. Actually, let us make the k-th vertex of a certain graph agree with each k-th state, and each of the non-zero transition probabilities P_{kj} — directed from the k to the j arc of the same graph. A structure of the matrix of vertex contiguity of the graph obtained will then be identical to the structure of matrix P and, consequently, the graph will determine the structure of the Markov chain imbedded in process {Y}.

As an example, let us consider a graph of the states and transitions of a passenger aircraft, subjected to routine preventive maintenance and repair during operation (Figure 42).

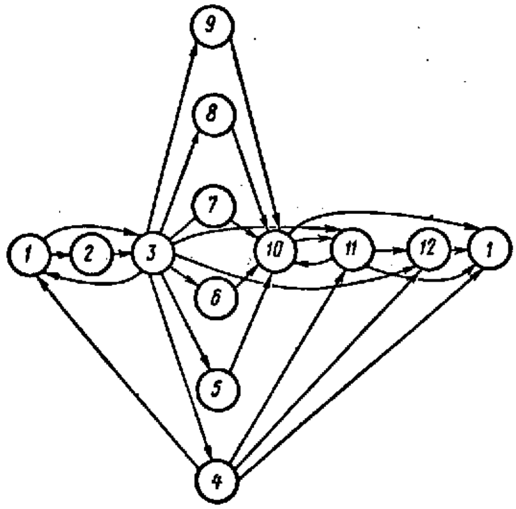


Figure 42. Graph of the states and transitions of a passenger aircraft during operation:

1- scheduled flight; 2- anticipation of beginning of maintenance; 3- flaw detection; 4- maintenance during brief idle period or post-flight maintenance; 5- form 1; 6- form 2; 7- form 3; 8- form 4; 9- major overhaul; 10- preflight maintenance; 11- operational readiness; 12- delay of takeoff.

The aircraft (system {Y}) spends some random time s_{1j}, distributed by the law $F_{1j}(s)$, in state 1, denoting flight, after /8 which it transfers with probability P_{1j} to one of the contiguous states j, for example, to a state of awaiting preventive maintenance, i.e., to state j=2. For convenience, such a transition is assumed to be instantaneous.

This process is semi-Markov. The characteristics of this process and its detailed mathematical description are given in [3].

The Wald Identity and Limiting Theorems of Renewal Theory

The Wald identity occupies a special place in renewal theory, because limiting theorems, important for applications, may be obtained by using it.

In order to obtain this identity, let us find the mathematical expectation of random value Z_s from equation (13).

From condition $Z_s \leq s$, we obtain

$$MZ_s = M \sum_{i=1}^{N+1} W_i = MW_1(MN_s + 1). \tag{15}$$

On the other hand, since $Z_s = z - U_z$ then

$$MZ_s = Z - MU_z. \tag{16}$$

Hence, from equation (15), we arrive at the Wald identity:

$$Z - MU_z = MW_1(MN_s + 1). \tag{17}$$

When deriving this identity, we assumed that all random values of W_i were distributed uniformly; therefore, $MW_i = MW_1 = T_w$. Expression (17) yields the following basic (of the limiting ones) theorems of renewal theory.

The elementary renewal theorem. For any law governing distribution of values W_i,

$$\lim_{z \to \infty} \frac{H(z)}{z} = T_w^{-1}. \tag{18}$$

Formally, this result is obtained from expression (17) by a direct limiting transition.

Using the elementary theorem, we may rather simply calculate the stationary values of the failure rate or renewals (see the theorem on parameter $\omega(z)$).

In practice the value of $\omega(z)$ is usually calculated where $z=1,000$ hours, assuming $K_{1000}=\omega(1000)$.

The Blackwell theorem. If W_i are distributed continuously and identically, then for any value of α, the following equality is valid /86

$$\lim_{z\to\infty}[H(z+\alpha)-H(z)]=\alpha T_w^{-1}. \quad (19)$$

Proof of this theorem is obtained immediately, if $z+\alpha$ is placed in expression (17) instead of z, if the calculation of the accumulation functions obtained, indicated in equality (19) is carried out, and if we pass to the limit.

Smith's theorem. For a monotonically non-increasing function $Q(z)$, integrable by $(0, \infty)$,

$$\lim_{z\to\infty}\int_0^z Q(z-u)\,dH(u)=T_w^{-1}\int_0^\infty Q(\tau)\,d\tau. \quad (20)$$

Smith's theorem is essentially one of the versions of Blackwell's theorem. Actually, if $Q(z)=\alpha^{-1}$ where $0<z\leq\alpha$ and $Q(z)=0$ in the remaining cases, we find equality (19) immediately from equality (20). The reverse derivation of (20) from (19) is also possible.

Taklind's theorem. If W_i has a finite dispersion σ^2_w, then

$$\lim_{z\to\infty}\left[H(z)-\frac{z}{T_w}\right]=\frac{\sigma_w^2}{2T_w^2}-\frac{1}{2}.$$

This theorem refines the elementary theorem and, generally speaking, is suitable for "younger" processes than those in (18).

The parameter ω(z) theorem. Under conditions similar to those of the preceding theorems,

$$\lim_{z\to\infty} \omega(z) = T_w^{-1}.$$

The use of limiting properties of renewal processes in many cases makes it possible to considerably reduce the necessary mathematical calculations.

Examples of Processes

1. Let x_n be the random accrued operating time of some machine or technical system between (n-1)-th and n-th failures, and let W_n be the expenditures (for example, in standard-hours) for correction of the n-th failure. We obtain a two-dimensional stochastic process in coordinates {accrued operating time — expenditures}.

2. Let x_n be random expenditures for maintenance of some machine, let us say, expenditures for preventive maintenance of an aircraft between two contiguous flights, and let W_n be the income from n-th flight. We again obtain a technical and economic model of a two-dimensional stochastic process.

3. Let x_n consist of expenditures for finishing operations during (n-1)-th preventive maintenance and for preparatory operations during n-th preventive maintenance of some system, let us say, expenditures for finishing and preparatory operations /87
in preventive maintenance of an aircraft between two of its contiguous maintenance periods. Moreover, let W_n be the "net" expenditures for repair (or checking of the efficiency) of the same system during n-th maintenance. We again obtain a two-dimensional stochastic process, but now in coordinates {expenditures — expenditures}.

The number of such examples may be increased considerably. All of them should provide an interpretation of random values of x_i and W_i such that the latter form a two-dimensional stochastic process.

2. The Function of Maintainability

Definition and Properties of the Function

Let us return to the process of accumulation (13) and further assume all values of W_i to be especially positive and distributed according to the same arbitrary law.

First, let us introduce the <u>distribution density</u> of random value W_i:

$$f_w(z) = \lim_{\Delta z \to 0} \frac{P\{z < W_i \leqslant z + \Delta z\}}{\Delta z}, \tag{21}$$

where $P\{z<W_i\leq z+\Delta z\}$ is the probability that the random moment of accumulation W_i is in the interval $(z, z+\Delta z)$.

Assume that maintenance of a system is performed and assume that W_i are random expenditures for i-th maintenance. Then $P\{z<W_i\leq z+\Delta z\}$ denotes the probability of being limited by expenditures to a single maintenance, not exceeding value z.

The distribution density satisfies the condition

$$\int_0^\infty f_w(z)\,dz = 1. \tag{22}$$

Let us call the <u>function of maintainability</u> of structures of the distribution function of value W_i, and let us calculate it as the probability that expenditures W_i on i-th maintenance of a system will not exceed the value of z, i.e.,

$$F_w(z) = P\{W_i \leqslant z\} = \int_0^z f_w(x)\,dx. \qquad (23)$$

Here $F_W(0)=0$ and $F_W(\infty)=1$, i.e., if as high expenditures as possible for maintenance of a system are permitted, any design is maintainable and, on the other hand, there are no designs of long-term utilization which do not require expenditures for maintenance and repair. In this case, expenditures may be understood in each specific case as expenditures of time, labor, or resources.

Let us call the loss function the expression /88

$$F_w(z) = P\{W_i > z\} = 1 - F_w(z) = \int_z^\infty f_w(x)\,dx. \qquad (24)$$

The distribution density of expenditures may be found as the derivative of the function of maintainability, if this function is known:

$$f_w(z) = F'_w(z) = -F'_w(z).$$

The flow parameter of accumulations of expenditures for maintenance is calculated by the expression

$$\omega_w(z) = \lim_{\Delta z \to 0} \frac{P\left\{z < W_i \leqslant z + \frac{\Delta z}{z} < W_i\right\}}{\Delta z}.$$

The conditional probability that maintenance of a system will be limited by expenditures within the range of z, z+Δz, provided that expenditures have already reached value z, is written in the numerator.

Returning to expressions (21) and (24) and using the formula for conditional probabilities, we find

$$\omega_w(z)=\frac{f_w(z)}{1-F_w(z)}=-\frac{F_w'(z)}{F_w(z)}.$$

As we can see, the flow parameter of accumulations of expenditures for maintenance is calculated only by the function of the maintainability of the system.

For cases where $\omega_W(z)$ is known, the function of maintainability may be calculated as

$$F_w(z)=1-\exp\left\{-\int_0^z\omega_w(x)\,dx\right\}, \tag{25}$$

or by the renewal function H(z)

$$F_w(z)=1-\exp\{H(0)-H(z)\}.$$

This result is obtained by substituting the values of $\omega(z)$ from (15) into formula (25) and makes it possible to rather simply estimate the function of maintainability with known estimates of H(z), calculated, for example, by formula (14).

Finally, direct differentiation of $F_W(z)$ from formula (25) yields the following for distribution density

$$f_w(z)=\omega_w(z)\exp\left\{-\int_0\omega_w(x)\,dx\right\}.$$

The function of maintainability is characterized by the following properties: /89

1. Where z=0, $F_W(0)=0$, and where $z\to\infty$, $F_W(\infty)=1$, i.e., when z varies from 0 to ∞, the function of maintainability varies from 0 to 1;

2. The loss function, which makes it possible to calculate, for example, the probability of overexpenditure of resources with respect to level z, may be calculated with the aid of the function of maintainability;

3. The function of maintainability makes it possible to calculate how stable the stochastic process is, which is especially important in investigating the stable characteristics of maintainability;

4. Such indicators, as the probability of correcting a failure within a given time, the probability that expenditures for spare parts will not exceed a given level, the average time required to correct a failure etc., may also be calculated with the aid of this function.

It should be noted that the function of maintainability, as one of the main indicators, fulfills the same role in the theory of maintainability as the function of reliability in investigating the dependability of systems and components.

The Relationship to the Function of Reliability

Let z=b be an equation of some straight line, parallel to the s axis and located at distance b from this straight line. In other words, let b be some fixed level of expenditures for maintenance of a system. Finally, let this straight line intersect process $\{s, z\}$ at point $\{S_b, b\}$, and let S_b denote the accrued operating time of the system to the b-th failure.

Since we are considering a strictly increasing accumulation process, $S_b > S = t$ if and only if $Z_s \leq b$. The foregoing is illustrated by Figure 43, and the condition makes sense in which routine switching on of a system is performed only upon completion of routine maintenance.

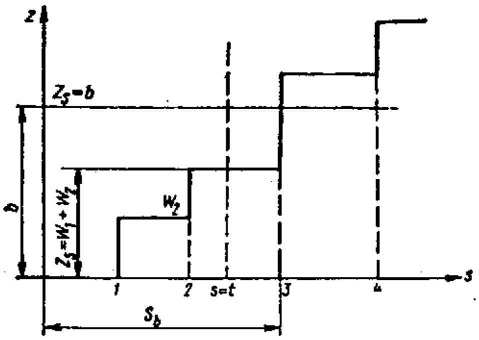


Figure 43. Calculation of the dependence between functions of reliability and maintainability.

Thus, we may now write the following for the probabilities:

$$P\{S_b > t\} = P\{Z_s \leqslant b\}.$$

Hence, from expressions (21) and (22), we have /90

$$\int_t^\infty f_s(v, b)\,dv = \int_0^b f_z(v, t)\,dv. \qquad (26)$$

Consequently, the maintainability of a system may also be calculated by its reliability with the aid of (26).

In order to illustrate the possibility of this approach, let us assume that values x_i and W_i are additive and are distributed exponentially with parameters ω_s and ω_w, respectively. For purposes of definition, let us also assume that Z_s is the accrued operating time of the system, and let us calculate s as the total calendar period between preventive maintenance cycles.

Using the notations from equation (26), we may obtain

$$f(s, b) = e^{-\omega_s s - \omega_w b} I_0(2\sqrt{\omega_s s \omega_w b}), \qquad (27)$$

where $I_0(y)$ is a zero-order Bessel function of the imaginary argument.

We may now find probability $P_1 = P\{Z_s \leq b\}$ by substituting expression (27) into equation (26). This yields

$$P_s = \int_0^b f_s(v, b)\,dv = \frac{\omega_s}{\omega_w} e^{-\omega_s s} \sum_{k=0}^{\infty} \frac{(\omega_s s)^k}{(k!)^2} \gamma(k+1, \omega_w b),$$

where

$$\gamma(k+1, \omega_w b) = k!\left[1 - e^{-\omega_w b} \sum_{m=0}^{k} \frac{(\omega_w b)^m}{m!}\right]$$

is an incomplete gamma function [8].

We note that always $\frac{\omega_s}{\omega_w} \leq 1$, since the accrued operating time of the system does not exceed the calendar time reserve. It is also interesting that

$$P_{s,w} = P\{Z_s \leqslant b\} + P\{Z_s > b\} = \int_0^{\infty} f_s(v, b)\,dv = \frac{\omega_s}{\omega_w}.$$

The probability

$$P_{s,w} = \frac{\omega_s}{\omega_w}$$

may be understood as one of the indicators of maintainability. In particular, if ω_s is the failure rate of some system after preventive repair has been performed, and ω_w is the same parameter prior to performance of such repair, then, where $\omega_s \leq \omega_w$, the stable probability $Q_{s,w} = 1 - P_{s,w}$ estimates the efficiency of maintenance.

If $\omega_s > \omega_w$, we estimate the probability $P_{w,s} = \frac{\omega_w}{\omega_s}$, since the processes of accumulation and renewal now change roles. In other words, if $\frac{\omega_s}{\omega_w} > 1$, either repair is inefficient, or the system is not adaptable for preventing failures during repair. In the first case the inequality $\frac{\omega_s}{\omega_w} > 1$ is obtained, if running-in failures occur after maintenance and, consequently, the modes or the /91 technological process of repair must be changed. In the second case, this inequality may be obtained when a system, which has undergone repair, is actually not adaptable to repair (for example, we cannot talk about the efficiency of repairing an electronic tube during its operation).

Relationship to the Renewal Function

The integral form for the accumulation function H(z) is obtained from equation (14) by using the formula of complete conditional mathematical expectation [10]. In this case we have

$$MN_z = \int_0^z M\left\{N_{z-w} + 1/W_1 = w\right\} dF(w) =$$

$$= F(z) + \int_0 M(N_{t-w})\, dF(w).$$

Using the notations from equation (14), we find

$$H_w(z) = F_w(z) + \int_0^z H_w(z-w)\, dF_w(w).$$

Similar discussions may be conducted for the renewal function

$$H_x(s) = F_x(s) + \int_0^s H_x(s-x)\, dF_x(x).$$

Attention should be given to the fact that for systems of long-term utilization $H_W(z)=H_X(s)$.

For the parameters of accumulation and renewal processe , respectively, we have: /92

$$\omega_w(z) = f_w(z) + \int_0^z \omega_w(z-w) f_w(w)\, dw;$$

$$\omega_x(s) = f_x(s) + \int_0^s \omega_x(s-x) f_x(x)\, dx.$$

Some Examples

1. Let Z_s=b be the expenditures which are planned for i-th maintenance of some system. A situation is possible in which the actual expenditures will exceed the planned expenditures. The expenditures for the completion of maintenance of the system V_w must be calculated.

Let us introduce the notation

$$m(z) = M(W_i - Z_s / W_i > Z_s), \tag{28}$$

where $W_i - Z_s = V_w$ is the previously mentioned "jump-over barrier Z," i.e., overexpenditure of funds for maintenance of the system.

Since expression (28) is the conditional mathematical expectation of random value V_w provided that $W_i > Z_s$, then, using the well known formula for conditional mathematical expectation [10], we may arrive at the expression

$$m(z) = F_w^{-1}(z) \int_z^{\infty} F_w(v)\, dv. \tag{29}$$

In the case of exponential distribution of random overexpenditure V_w, we have from expressions (24) and (25)

$$F_w(z) = e^{-\omega z},$$

where ω is the rate of accumulation of expenditures for maintenance, considered as the average number of maintenances, required per unit expenditures. Consequently, $m(z)=\frac{1}{\omega}$.

2. Under the conditions of the first problem, we find the mathematical expectation of "jump-under to barrier Z" (the saving of expenditures $U_w=Z_s-W_i$), i.e.,

$$C(z) = M(\tilde{Z} - W_i | W_i < Z_s).$$

Using the scheme of solving the preceding problem, we now obtain

$$C(z) = F_w^{-1}(z) \int_0^z F_w(u)\, du. \qquad (30)$$

For the exponential distribution law U_W, we have

$$C(z) = \frac{1}{\omega}.$$

3. Under the conditions of the first two problems, we find the average expenditures for a single complete maintenance T_W.

From expressions (29) and (30), we immediately obtain /9

$$T_w = m(z) F_w(z) + C(z) F_w(z) = \int_0^\infty F_w(z)\, dz.$$

In the exponential case

$$T_w = \int_0 e^{-\omega z} dz = -\left(\frac{1}{\omega} e^{-\omega z}\right) = \frac{1}{\omega}.$$

Relationship to the Methods of Aircraft Maintenance and Repair

The values of the maintainability indices, considered in the first chapter, and also the function of maintainability are calculated not only by the constructive solutions of aircraft systems, but by the methods of their maintenance and repair. Therefore, it is important to know when developing an aircraft how the method of its maintenance and repair affects the values of the maintainability indices.

Let us consider this problem with the example of the maintainability function.

According to the previously given definition, we have for this function

$$F_x(s)=\int_0^s f_x(x)\,dx,$$

where $f_x(s)$ is the distribution density of random value S_i.

We note from this expression that the value of the area, bounded by curve $y=f_x(s)$ on the segment between 0 and s, depends on the shape of curve $y=f_x(s)$. This denotes, in particular, that even if the mathematical expectations of expenditures for maintenance and repair are equal under different laws $f_{1x}(s)$ and $f_{2x}(s)$, i.e., where $\int_0^\infty xf_{1x}(x)\,dx=\int_0^\infty xf_{2x}(x)\,dx$, the values of the maintainability function may be different

$$F_{1x}(s)\neq F_{2x}(s). \tag{31}$$

It follows from this that, to evaluate the maintainability of an aircraft, it is sufficient in a number of cases to calculate only the average values of the technological characteristics. Moreover, this denoted the possibility of controlling the level of maintainability with the aid of procedures which do not require constructive changes.

One of these procedures may be a change of the method or technological process of maintenance and repair of an aircraft. /94
Actually, the law $f_{1x}(s)$ may denote, for example, the distribution density of random value S_i until the procedure or technological process is changed, and $f_{2x}(s)$ may denote the same thing after they have been changed.

If the form of laws $f_{1x}(s)$ and $f_{2x}(s)$ is known, it is easy to establish the precise sign of inequality (31) and to find in this manner the efficiency of changing the method or technological process of maintenance and repair. In order to make the argument more specific, let us consider two possible methods of maintenance and repair: 1- replacement and repair of the units of a system strictly according to the accrued operating time of the designated lifetime and 2- replacement and repair of units according to their technical condition.

According to the first method, maintenance replacement and repair are carried out for a specific set of assemblies and units of aircraft systems. In this case, the number of repair operations for a specific type of maintenance is always constant, although the amount of work for each of the operations is random.

In the second case, the number of operations of routine repair is calculated from the results of preliminary inspection of the technical condition, as a result of which the actual requirement for maintenance replacement and repair of one or another unit is determined.

Let us now pose a problem, which includes determination of the function of maintainability in the first and second cases, and indicate which of the methods of maintenance and repair is more efficient.

Let a system consist of a rather large number of subsystems and be subject to maintenance and repair initially according to the first, and then according to the second method.

In the first method of maintenance and repair, the total random length of the operation will be

$$S_n = \sum_{i=1}^{n} x_i,$$

where n is the number of subsystems subject to maintenance.

If the values of n are sufficiently large, as is known, the sum of the independent random values is distributed asymptotically normally according to the central limiting theorem (see, for example, [24]).

In the second method, replacement of the units and repair of them is carried out according to the results of preliminary inspection with probability p, and is not performed with probability q=1-p.

Consequently, the total length of the operation will be

$$S_N = \sum_{i=1}^{N} x_i,$$

where N is the random number of repair operations.

Since the number of terms of N in this expression is a random value, the conditions for the central limiting theorem are disrupted. /95

Now, if N is distributed, let us say, according to Pasqual's law, $P\{N=k\}=pq^{k-1}(k=1, 2, \ldots)$, where $q=1-p(0<p<1)$, the limiting theorem for rarefied flows comes into force.

This theorem stipulates that, if an ordinary stationary Palma flow is rarefied sequentially a sufficiently large number of times, then such a repeatedly rarefied flow will be close to the simplest flow [16].

It is easy to prove that higher maintainability indices of aircraft systems are provided using the second method of replacement and repair of the units.

As before, let us denote by T_x the mathematical expectation of value x. Then $MS_n = nT_x$ and $MS_N = MNT_x$. But $MN \leq n$ according to determination of the second method of maintenance and, consequently

$$MS_n \geqslant MS_N.$$

Let us now compare the values of the function of maintainability for the first and second methods of replacement and repair of units of a system at points $s=MS_n$ and $s=MS_N$.

Since $F_{1x}(s)$ has normal distribution, $F_{1x}(MS_n)=0.5$. $F_{2x}(s)$, according to [16], has exponential distribution, for which $MS_N=\frac{1}{\lambda}$. Consequently, $F_{2x}(MS_N)\approx 0.63$.

In other words, under similar equal conditions

$$F_{2x}(MS_N) > F_{1x}(MS_n)$$

independently of the variation of the term N.

Thus, a higher value of the maintainability function is guaranteed when using the second method of replacement and repair of the units of a system.

In conclusion, we note that if the system is not adaptable to progressive methods of maintenance and repair and, in particular, the replacement and repair of units according to their technical condition, in this case such methods of maintenance cannot be implemented, and the labor expenditures for maintenance and repair of the system increase sharply.

3. The Use of Correlation Analysis for Evaluation of Maintainability

Previously, when considering the two-dimensional random process, we assumed that the values of x_i and W_i, respectively, were mutually independent in renewal process (12) and the accumulation process (13). Nevertheless, when solving many important problems of maintainability of structures, the class of processes with a stochastic ratio between their elements may be useful. Correlation analysis may be used to investigate certain characteristics of such processes.

The main task of correlation analysis, as is well known, is to study and measure the dependence of random values and events. Observations or experiences with measurements of these random values are necessary to study the effect of one value x on another value y.

In correlation analysis, the dependence of conditional means of $\bar{y}_x$ on x or $\bar{x}_y$ on y are studied. In this case, it should be kept in mind that in practice we are often concerned with variation of the value of x, for example, within such a limited range that variation of $\bar{y}_x$ in it is reflected rather closely by the segment of a straight line. Therefore, in further discussing the material, we will conditionally assume that the function which expresses the variation $\bar{y}_x$ as a function of x, is linear or close to it.

Two Theorems of Correlation Analysis

The following two theorems of correlation analysis are used as the main theorems with respect to this problem [24].

Theorem 1. The mathematical expectation of multiplying two random values x and y is equal to the sum, comprised of the product of the mathematical expectations and the product of the mean square deviations of these values

$$M(xy) = MxMy + r\sigma_x\sigma_y. \tag{32}$$

Theorem 2. The dispersion of the sum S_n of random values comprises the sum of dispersions and the sum of the products of the paired correlation of the sum by the corresponding pairs of mean square deviations

$$DS_n = \sum_{i=1}^{n} Dx_i + \sum_{i \neq k}^{n} r_{x_i x_k} \sigma_{x_i} \sigma_{x_k}.$$

Definition of a Complex Technical System

Let us now give a somewhat different definition of a complex technical system.

Let us consider a certain combination of n cells and another combination of n units. Let us assume that the units and cells are numbered and that the i-th unit may be placed in j-th cell /9 (i, j=1, 2, 3, ..., n). In the latter case, we will say that the unit occupies the cell.

The combination of cells and units, for which all units are distributed in the cells, and the parameters which agree with each cell and each unit are called a complex technical system.

This definition of a system makes it possible to take into account the different variants of distribution of units in the cells of a system and makes it possible to apply correlation analysis to investigation of it.

Actually, by relating some standardized random expenditures Φ_j for preventive maintenance of an occupied cell to a j-th cell, for example, and by relating some standardized random characteristic of it, let us say, K_i, to the i-th unit, we may now construct random two-dimensional processes $\{\Phi, K\}$, using the statistical characteristics of the random values for this.

We can show that the correlation coefficient may in similar cases be the measure of the maintainability of the design.

The Scheme of Development of the Correlation Relationship Between the Accumulation and Renewal Process

The scheme of development of correlation may be presented in the following manner.

Let x_i and W_i be independent and form a two-dimensional process $\{S, Z\}$, and let T_w and σ_w^2 denote the average value and variance of W_i. Since, by definition, W_i are distributed identically, we may write the following [12]:

$$M(Z_t|N_t = n) = nT_w;$$

$$D(Z_t|N_t = n) = n\sigma_w^2.$$

Hence, it follows that correlation for independent process $\{X_i\}$ and $\{W_i\}$ occurs between values Z_t and N_t, rather than between values x and W.

To calculate the correlation coefficient between processes $\{Z_t\}$ and $\{N_t\}$, let us use the first theorem of correlation analysis (32), according to which we have

$$r = \frac{MZ_tN_t - MZ_tMN_t}{\sigma_z\sigma_N}, \tag{33}$$

or

$$r = \frac{MZ_tN_t - MZ_tMN_t}{\sqrt{DZ_tDZ_t}} \tag{34}$$

As is well known [24], the correlation coefficients of values Z_t and N_t may be calculated by covariation of these same values:

$$r = \frac{\mathrm{Cov}(Z_tN_t)}{\sqrt{DZ_tDN_t}},$$

where $\mathrm{Cov}(Z_tN_t) = M(Z_tN_t) - MZ_tMN_t$.

The correlation coefficient has the following main properties.

1. It may be both a positive and negative number or equal to zero. In positive correlation, the process of accumulation increases monotonically, intersecting some given level from the bottom upwards at a single point. In negative correlation, the process decreases monotonically as N_t increases.

2. The correlation coefficient does not exceed ±1. If $r = \pm 1$, there is a precise linear dependence between Z_t and N_t.

3. The correlation coefficient is equal to zero, if and only if Z_t and N_t are independent.

Our considered scheme of development of the correlation relationship between random values Z_t and N_t is the simplest.

In more complex cases, when, for example, function $\bar{y}_x$ of x is nonlinear, the correlation ratio must be calculated, because the correlation coefficient cannot be a measure of the closeness of the relationship. The correlation function is calculated when investigating the correlation between random functions in a stochastic process [21].

However, calculation of the correlation coefficient is sufficient in most cases for the simplest problems of estimating maintainability.

Calculating the Correlation Coefficient

Let us present without proof the basic formulas for calculation of the correlation coefficient [20].

1. The unbiased estimate of mathematical expectations of Mx and My may be the empirical averages

$$\bar{x} = \frac{1}{n} \sum_{i=1}^{n} x_i \tag{35}$$

and

$$\bar{y} = \frac{1}{n} \sum_{i=1}^{n} y_i, \tag{36}$$

where x_i and y_i are the realization of random values x and y; n is the number of realizations.

2. The unbiased estimate of dispersions of $\sigma_x{}^2$ and $\sigma_y{}^2$ may be the empirical variances

$$S_x^2 = \frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{n - 1} \tag{37}$$

and

$$S_y^2 = \frac{\sum_{i=1}^{n} (y_i - \bar{y})^2}{n-1} \tag{38}$$

3. The unbiased estimate of covariation of the random values is given by the formula

$$\text{Cov}(xy) \approx \frac{\sum_{i=1}^{n} (x_i - \bar{x})(y_i - \bar{y})}{n-1} \tag{39}$$

4. The empirical estimate of the correlation coefficient is obtained from formulas (35)-(39):

$$\hat{r} = \frac{\sum_{i=1}^{n} (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n} (x_i - \bar{x})^2} \sqrt{\sum_{i=1}^{n} (y_i - \bar{y})^2}} \tag{40}$$

The value r is called the <u>selective correlation coefficient</u>.

The equation for the selective direct regression y by x may now be written in the form

$$y - \bar{y} = \hat{r} \frac{S_y}{S_x} (x - \bar{x})$$

and the equation of selective direct regression of x by y is

$$x - \bar{x} = \hat{r} \frac{S_x}{S_y} (y - \bar{y}).$$

<u>Example</u>. A radio navigation system, consisting of six units, is under controlled operation on a group of aircraft. The results of statistical examination of the system are presented in Table 18, where $K_{1000}=\omega(1000)$ denotes the number of failures

of the units occurring per 1000 hours of operation, and Φ is the time required for correcting the failures (replacement of the unit).

TABLE 18.*

No. of unit	K_{1000}	Φ, min	$K_{1000}\Phi$
1	0,234	105	24,57
2	0,358	100	35,80
3	0,265	120	31,80
4	0,078	110	8,58
5	0,452	135	61,02
6	0,0624	140	8,74
Average	0,242	118,3	28,4

*Translator's note: Commas in the numbers represent decimal points.

The maintainability of the system must be evaluated by calculating the correlation coefficient between K_{1000} and Φ.

Using formulas (37) and (38), we have DK_{1000}=0.02 and $D\Phi$ = 227.6. /100

Assuming $Z_t = K_{1000}$ and $N_t = \Phi$, we find from equation (34) the value of the correlation coefficient:

$$r=\frac{28,4-0,242\cdot 118,3}{0,02\cdot 227,6}=-0,094.$$

The equation of regression accordingly has the form (Figure 44): $K_{1000} = 0.252 - 0.0000875\ \Phi$.

As we can see, the correlation coefficient is negative in the given case and its absolute value is negligibly small. This means that, at the existing level of unit dependability, their distribution by cells has not been carried out in the best manner.

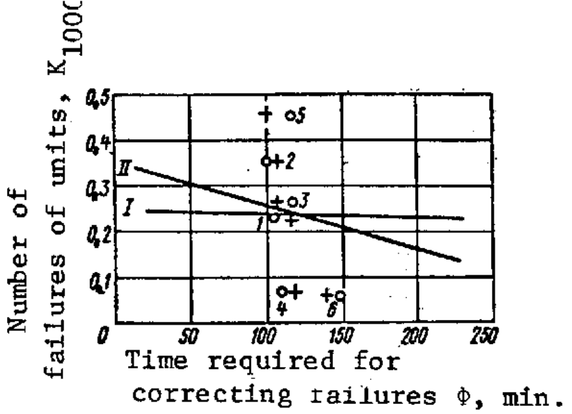


Figure 44. Calculation of the correlation coefficient:
I- line of regression $K_{1000} = 0.252 - 8.75 \cdot 10\ \bar{\Phi}$ with the initial variant of arrangement of units 1, 2, 3, 4, 5, and 6 (denoted by the circles); II- line of regression ($K_{1000} = 0.34 - 8.3 \cdot 10^{-4}\ \Phi$) after optimization of unit arrangement (denoted by the crosses).

4. Elementary Theorems of the Maintainability of Designs

The definition given above for a complex technical system as a combination of cells and units — for which all units are distributed in cells, and some parameters are in agreement with each cell and unit — makes it possible to successfully solve certain problems of optimum stochastic design.

Let $M\Phi_i$ and MK_i be the mathematical expectations of the corresponding random values for which we now assume that $M\Phi_i$ and MK_i vary randomly from subscript to subscript. This approach is quite obvious, since we may always assume that the design of a system is combined with a random search for the best variant.

Let us introduce the notations $\varphi_i = M\Phi_i$ and $k_i = MK_i$. Let $\bar{\varphi} = M\varphi_i$ and $\bar{k} = Mk_i$ be the means of random values φ_i and k_i, and let $D\varphi$ and Dk be the variances of the same values. Let us now write the theorem of correlation analysis (32) in the form

$$\overline{\varphi k} = \bar{\varphi}\bar{k} + r\sigma_{\varphi}\sigma_{k}. \tag{41}$$

Assume

$$\varphi_1 \geqslant \varphi_2 \geqslant \varphi_3 \geqslant \dots \geqslant \varphi_n \tag{42}$$

and

$$k_1 \leqslant k_2 \leqslant k_3 \leqslant \dots \leqslant k_n. \tag{43}$$

Then (and only then), according to Chebyshev's inequality [13], we have

$$\overline{\varphi k} \leqslant \overline{\varphi k}. \tag{44}$$

Comparing expressions (44) and (41) and noting that always $\sigma_\mu > 0$ and $\sigma_k > 0$, we find that under the conditions of (42) and (43) the correlation coefficient should in turn satisfy the condition

$$-1 \leqslant r \leqslant 0.$$

But since $\bar{\bar{\varphi}}k$ is expenditures for maintenance of a system with non-random disposition of units in cells, and $\bar{\varphi}k$ — the same type of expenditures, but with arrangement of units in the system with selection of cells at random, we may now formulate the first theorem of maintainability.

Theorem 1. Under conditions (42) and (43), the correlation coefficient r is negative or equal to zero, and expenditures for maintenance of a system are less than in any method of arranging units in terms of cells, and are calculated by inequality (44).

The physical sense of the theorem becomes especially understandable if we assume that the cost of maintenance of i-th unit in j-th cell depends only on the number of the cell (for example, expenditures for accessibility. Then, by filling a "cheaper" cell by a more reliable unit in the sense of maintenance, we can design a system, whose expenditures for maintenance are calculated by inequality (44).

Theorem 2. Disposition of units in the cells of a system according to conditions (42) and (43) is optimum in the sense that any other method of unit disposition increases maintenance expenditures.

In order to prove this theoremm, it is sufficient to change the places of any two, let us say, φ_i and φ_{i+1} elements in expressions (42) or (43) and to find that the new expenditures for maintenance increase. Let us set $\varphi_{i+1}=\varphi_i'$ and $\varphi_i=\varphi_{i+1}'$. From expressions (42) and (43), we obtain two sequences $\varphi_i'\leq\varphi_{i+1}'$ and $k_i\leq k_{i+1}$. But the Chebyshev inequality now reverses sign for these sequences, i.e., expenditures for maintenance of a subsystem, formed by rearranged units, become greater than under condition $\varphi_i'\geq{}_{i+1}$. Since the expenditures are additive, the expenditures for maintenance of the entire system increase and, consequently, rules (42) and (43) yield the optimum variant of the design in the sense of the maintenance cost. /10

We note that the correlation coefficient in the given means and variations of $\bar{\varphi}$, $\bar{k}$, $D\varphi$ and Dk of random values φ_i and k_i may be a measure of maintainability, because only correlation coefficient r may be calculated instead of the function of maintainability $P\{\overline{\varphi k}\leq\overline{\varphi k}\}$.

Moreover, it is not necessary to know the laws governing distribution of values φ and k, but only their numerical characteristics must be known. Finally, during the first stage, when information about the sign of r must be known, in a number of cases it is unnecessary to carry out calculations: it is sufficient to construct the empirical line of regression. If this line has a tendency to increase, $r>0$ and the system design is clearly not maintainable. If the slope of this line is negative, the correlation coefficient $r<0$ and it should be calculated by formula (40).

If r_d is the direct value of the correlation coefficient, and as a result of calculation $|r|<|r_d|$, the design should be regulated according to theorem 1. Such regulation, as follows from theorem 2, will be optimum.

Example. Under the conditions of the example given in the preceding section, the best variant of arranging the units in a radio navigation system must be indicated.

Let us use theorem 1 to solve this problem. According to this theorem, the most unreliable unit should be located in a cell which requires the least expenditures for maintenance or replacement of the unit. Using this rule, we arrive at the following scheme of arranging the units (Table 19). In this case, expenditures for all cells remain unchanged.

TABLE 19.*

No. of unit	K_{1000}	Φ, min	$K_{1000}\Phi$
1	0,234	120	28,08
2	0,358	105	37,59
3	0,265	110	29,15
4	0,078	135	11,53
5	0,452	100	45,2
6	0,0624	140	8,74
Averages	0,242	118,3	26,71

Repeating the scheme of calculations used in the preceding example, we find the means and variations of values K_{1000} and Φ.

For the correlation coefficient, we obtain in the given case the value

$$r = \frac{26,71 - 0,242 \cdot 118,3}{0,02 \cdot 227,6} = -0,89,$$

and the equation of regression will have the form (see Figure 44)

$$K_{1000} = 0,34 - 8,3 \cdot 10^{-4} \Phi.$$

Thus, the average expenditures for correcting failures in units $K_{1000}\Phi$ become less (26.71 compared to 28.4 in the preceding example), and the absolute value of the correlation coefficient is almost ten times higher than the previous one.

In the given example, we have taken into account the presence of possible functional or other relationships between the units and have conditionally assumed that any unit of the system may be placed in any cell of the number available. Moreover, in individual cases such relationships should be taken into account. A similar definition of a complex system is used, in particular, in [34], and an algorithm for its optimization is proposed for the case when the units of a system are related to each other by some law and the graph which takes into account this relationship is known. /10

5. Simulation in Problems of Maintainability

In some cases, for example, during the stages of developing the design of some complex technical system, the only method of analysis and calculation of values of the indicators of its maintainability may be simulation.

Actually, when developing new designs, the required statistical data are lacking, and it is impossible to determine the best design variant by ordinary methods in terms of maintainability. At the same time, the information from the theory of maintainability of systems, given above, makes it possible to considerably facilitate the search for optimum variance of arrangement of the units of a system according to its cells, using simulation methods. In this case, it is feasible to consider two possible cases of maintainability optimization according to the given (directive) correlation coefficient r_d.

In the first case, the average expenditures $\overline{K\Phi}$ for maintenance of the units of a system may be given. It is necessary to calculate the values of K_i for each i-th unit of the system in such a manner that condition $|\hat{r}| \geq |r_d|$ is satisfied.

In the second case, the values of K_i may be assumed to be given, and it is necessary to calculate the average expenditures $\overline{K\Phi}$ for maintenance of a system such that condition $|\hat{r}| \geq |r_d|$ remain valid.

Each of these problems may be solved both on the basis of physical and statistical methods of simulation. /104

Let us first consider one of the variants of solving the problem for finding such a design which would more completely satisfy the directive value of the correlation coefficient. Since this problem is related to investigation of variants, the correlation coefficient must be calculated at least twice for each new variant of the design.

It is easy to calculate the correlation coefficient. However, such calculations are cumbersome even with a small amount of initial data, and therefore errors may be committed during the calculation, especially during manual calculations or in calculations on a calculator while making intermediate notations on paper.

On the other hand, it is well known that computer calculations are rather expensive and, together with preparation of initial data for simple systems, require greater expendituеs of time and resources than in any other method of calculation. Therefore, a specialized portable analog device, which makes it possible to calculate the correlation coefficient directly on the drawing board of the designer, involved in solution of problems of configuration and arrangement of units and finished components on an aircraft, may be recommended as an answer to the problem.

Let us consider an enlarged functional diagram of this device (Figure 45). Signals, proportional to parameters K_i, Φ_i and $K_i\Phi_i$, are fed into the inputs of the corresponding URPET units with outputs of i-th parameter generators (PG). Blocks $\bar{K}$, $\bar{\Phi}$ and $\overline{K\Phi}$ convert signals K_i, Φ_i and $K_i\Phi_i$ according to formulas (35) and (36) and according to the principle of operation, are ordinary summation devices of the input signals.

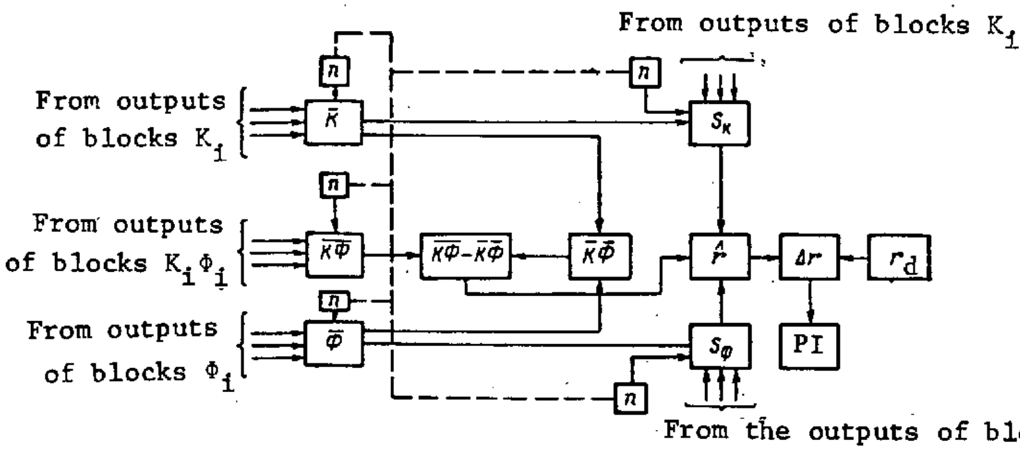


Figure 45. Functional diagram of a device for calculation of maintainability parameters (URPET).

Such summation is accomplished by sequential combination of the corresponding PG outputs. Division of the added signals by n — i.e., by the number of units of the system being designed — is accomplished, with the aid of a resistor voltage divider, by installation of a switch of units n in the necessary position. /105

From the outputs of blocks $\overline{K}$ and $\overline{\Phi}$, the signals enter the amplification block $\overline{K}\overline{\Phi}$, at the output of which is formed the voltage, proportional to the value of $\overline{K}\overline{\Phi}$. This voltage is fed into the comparator block $\overline{K\Phi} - \overline{K}\overline{\Phi}$ and is compared with the voltage obtained at the output of block $\overline{K\Phi}$. In the case when $\overline{K\Phi} - \overline{K}\overline{\Phi} < 0$, a negative signal is developed, and if $\overline{K\Phi} - \overline{K}\overline{\Phi} > 0$, a positive signal is developed. The voltage, proportional to the value $\overline{K\Phi} - \overline{K}\overline{\Phi}$, is fed into the correlometer $\hat{r}$, into the two other inputs of which are fed the signals, proportional to the mean-square values S_k and S_Φ, calculated by formulas (37) and (38).

Correlometer $\hat{r}$ develops a signal, proportional to the value of the correlation coefficient $\hat{r}$ (formula 40) and transmits it to the input of the zero member Δr. A signal, proportional to the directive value of the correlation coefficient r_d from block r_d, is fed to the second input of this same zero member. The necessary level of this signal is established with the aid of a potentiometer lever, which is the main unit of block r_d.

A signal, proportional to the difference of $\Delta r = \hat{r} - r_d$, enters the pointer indicator PI with zero in the middle of the scale and the fulfillment or nonfulfillment of condition $|\hat{r}| \geq |r_d|$ may be judged by the deflection of its pointer.

Thus, if $\Delta r > 0$, this condition is fulfilled and the directive requirements for the maintainability of the system are assumed to be observed. In the opposite case, either the values of K_i or the values Φ_i must be varied as a function of the initial data. The operator carries out such variations with the aid of the PG control members (Figure 46).

Blocks K_i and Φ_i are ordinary voltage dividers, and block $K_i\Phi_i$ is an analog multiplier. By changing the positions of the

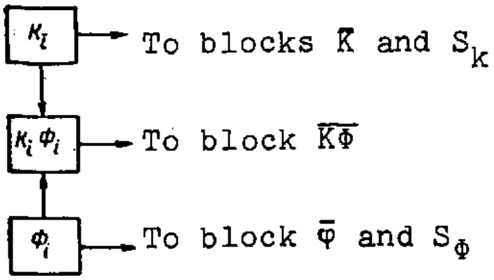


Figure 46. Functional diagram of PG.

control members of blocks K_i and Φ_i, equipped with numbered dials, the voltages fed to the inputs of blocks $\bar{K}$, $\bar{\Phi}$, $K_i\Phi_i$ and $\overline{K\Phi}$, may be changed.

Afterwards, the obtained values of K_i or Φ_i, for which condition $|\hat{r}| \geq |r_d|$ is fulfilled, may be taken from dial K_i or Φ_i.

Let us now consider one of the possible variants of solving the problem for optimization of maintainability by the statistical /106 modeling method.

A block diagram of an algorithm for selection of the optimum maintainability variant of unit arrangement by cells of the system being designed is presented in Figure 47. The distribution /107 functions $F_i(x)$ and $F_i(y)$ of the time x_i of no-failure operation of the i-th unit and of the time y_i required for correction of the failure or the time required for maintenance of this unit should be given as initial data for solution of the problem in this case. Moreover, the directive value of the correlation coefficient r_d, the number of units of system n, the number of systems M_i, providing reliable statistics according to the i-th block, the total operating life of the block T_i and the number of planned maintenances N_p during time T_i should also be given.

The program will be as follows. At the beginning of the calculation, we set i=0, and calculation of values K_i and Φ_i is

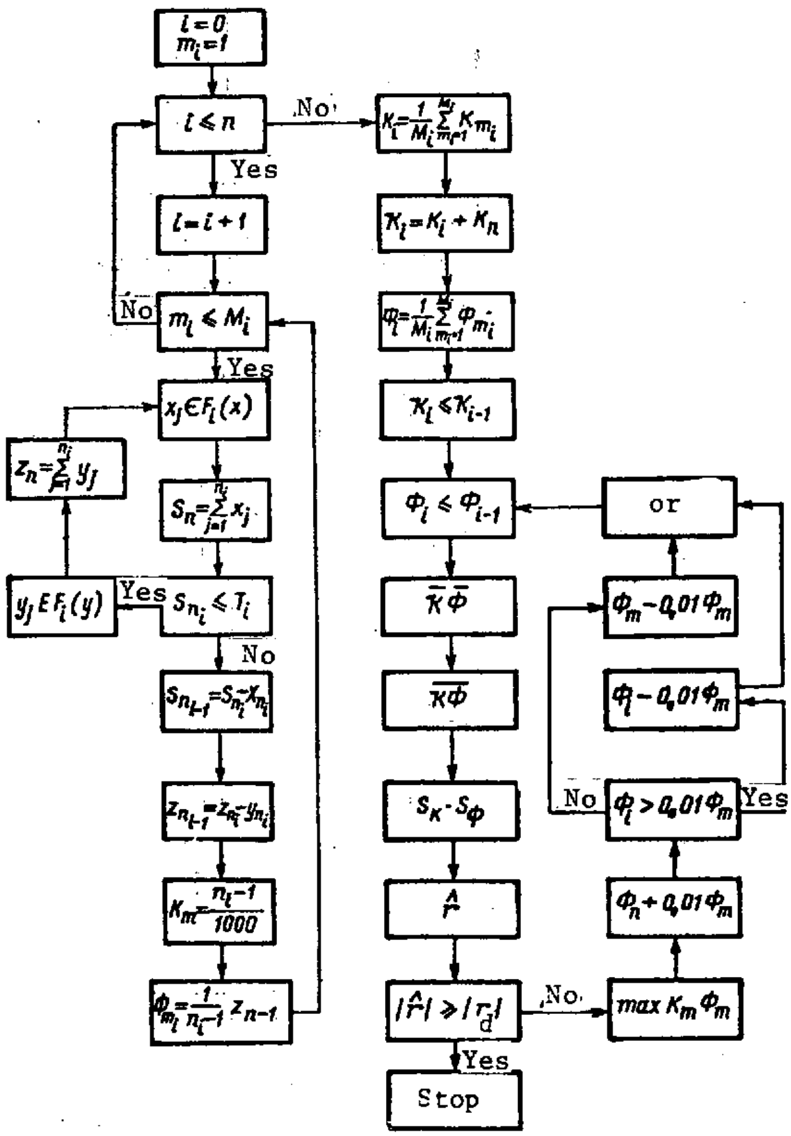


Figure 47. Block diagram of an algorithm for optimizing the maintainability indices according to the given directive correlation coefficient.

carried out for the first unit of the system being designed. The number of realizations m_i of random values x_i and y_i is equal to unity in this case.

Operator $i \leq n$ checks the condition $i \leq n$ and, if this condition is fulfilled, then operator $i=i+1$ for the old value $i=0$ is added to unity and control is transferred to operator $m_i \leq M_i$, which controls the number of realizations of random values x_i and y_i for unit $i=1$.

If condition $m_i \leq M_i$ is fulfilled, then operator $x_j \in F_i(x)$ generates realization x_j of random values x_i, distributed according to the law $F_i(x)$. In operator $S_{n_i} = \sum_{j=1}^{n_i} x_j$ the random values of x_j are added and then a check of condition $S_{n_i} \leq T_i$. If this condition is fulfilled, operator $y_j \in F_i(y)$ generates realization y_i of random value y_i, distributed according to the law $F_i(y)$, and operator $Z_{n_i} = \sum_{j=1}^{n_i} y_j$ fulfills the addition of realizations of y_j.

Control is again transferred to operator $x_j \in F_i(x)$, and the cycle is repeated until the i-th unit of the system "exhausts its operating life" T, i.e., until condition $S_{n_i} \leq T$ is fulfilled. If this condition is violated, operators $S_{n_i-1} = S_{n_i} - X_{n_i}$ and $Z_{n_i-1} = Z_{n_i} - Y_{n_i}$ decrease the values of S_{n_i} and Z_{n_i}, respectively, by values X_{n_i} and Y_{n_i}. In other words, it is assumed that failure of the system may not occur within the limits of its total operating life. Coefficient $K_{m_i} = \frac{n_i - 1}{1000}$ is then calculated with the aid of the corresponding operators, and the average time required for correction of a single failure $\Phi_{m_i} = \frac{1}{n_i - 1} Z_{n_i-1}$ for the i-th unit of the system and control is again transferred to operator $m_i \leq M_i$. If condition $m_i \leq M_i$ is not fulfilled, control is transferred to operator $i \leq n$, after which the entire cycle is repeated for unit $i=2$ etc. up to disruption of condition $i \leq n$.

In this case, control is transferred to a group of operators, which calculate the selective correlation coefficient $\hat{r}$.

It should also be noted here that the total number of k_i removals of the i-th unit of the system for repair or maintenance is formulated with the aid of operator $k_i=K_i+N_p$ instead of K_i. In this case it is conditionally assumed that the average expenditures Φ_i for unscheduled repair or routine maintenance remain fixed. If this assumption is invalid, instead of operator $\Phi_i=\frac{1}{M_{i_m}}\sum_{i=1}^{M_i}\Phi_{m_i}$, operator $\Phi_i=\frac{1}{M}\sum_{m_i=1}^{m=1}\Phi_{m_i}+\varphi_i$ (φ_i is the correction for the average expenditures introduced in connection with the performance of routine preventive maintenance) should be introduced.

Operator $k_i \geq k_{i-1}$ forms a decreasing series of coefficients k_i and provides their reindexing by rank from left to right.

Operator $\Phi_i \leq \Phi_{i-1}$ forms an increasing series of values Φ_i and carries out their reindexing by the same principle.

Further, the means for indexes $\bar{k}$, $\bar{\Phi}$ and $\overline{k\Phi}$, as well as the mean-square values of S_k and S_Φ are calculated according to the new indexing of elements k_i and Φ_i. Finally, operator $\hat{r}$ performs calculations of correlation coefficient $\hat{r}$ according to formula (33) or (34). The first stage of optimization of maintainability of the system being designed terminates with this step.

In the second stage operator $|\hat{r}| \geq |r_d|$ compares the obtained value of correlation coefficient $\hat{r}$ with the directive correlation coefficient r_d. If the modulus of coefficient $\hat{r}$ is less than that of r_d, the second stage of optimization ends with this step.

In the opposite case the maximum value of Φ_m is calculated and selected by index m from the series of values $K_i\Phi_i$ with the aid of operator max $K_m \Phi_m$. Afterwards, operator $\Phi_n + 0.01\Phi_m$ increases the cost of maintenance of the n-th unit, i.e., the most reliable unit, by value 0.01 Φ_m, and operator $\Phi_j - 0.01\Phi_m$ decreases the cost of maintenance of the more reliable unit, but the same value provided that $\Phi_i > 0.01\Phi_m$. If this condition is not fulfilled for all values $i<m$, operator $\Phi_m - 0.01\Phi_m$ is switched on. In any case the OR operator, with the aid of which is provided a new cycle of calculating the correlation coefficient $\hat{r}$, becomes operable

The calculations are completed if $|\hat{r}| \geq |r_d|$. In this case, at the command of operator STOP the values of k_i, Φ_i; $\bar{k}$, $\bar{\Phi}$, $k\Phi$, S_k, S_Φ and r are printed out in a sequence, determined by operator $k_i \geq k_{i-1}$. Knowing these data, the units must be disposed in the cells according to the sequence found and must provide cost Φ_i.

We note that other algorithms may be minimized, for example, $\overline{k\Phi}$ with given $\bar{k}$ and $\bar{\Phi}$ or $\bar{\Phi}$ with given $\overline{k\Phi}$ etc. We also note that the step of optimization, equal to $0.01\Phi_m$, used in the algorithm, may be enlarged and then the search for the optimum variant will be completed within a fewer number of steps, but with less accuracy. /10

CHAPTER 4

CALCULATION OF THE INDICATORS AND ASSESSMENT OF MAINTAINABILITY

1. Fundamental Aspects

In order to assess the maintainability of an aircraft design at the modern level of development of aircraft building, it is insufficient to be limited by its qualitative characteristics, but there must be quantitative calculation of indicators. The necessity of quantitative calculation and analysis of maintainability of a design arises during development of the specifications for a new aircraft prototype, during selection of several possible design variants as the best one, during consideration of several "competitive" designs of components of the same designation, and also during consideration of the model and conducting of tests of the experimental prototype.

In the general case, calculation of maintainability should include determination of all indicators and characteristics given in the first chapter of the book and used in assessment of maintainability.

The main method of calculating the indicators of maintainability during the stages of design and manufacture of aircraft should apparently be the analytical method, and during the stages of testing and operation it should be the statistical method. In a number of cases calculation of indicators during the test and operational stages is called experimental determination of maintainability.

It should be noted immediately that analytical methods of calculating the indicators of maintainability have not yet been completely and adequately developed and we will not consider them here in detail.

The methods of calculating (experimental determination) the indicators of aircraft maintainability during the testing and operational stages are becoming more widely used. They are based on the use of statistical data on maintenance procedures and routine repair, obtained in operational and repair enterprises. /110

The main statistical data, required for calculation, include:

- the existing operating lifetime of the aircraft, its assemblies and apparatus;
- the types of maintenance and repair and the frequency of performing them;
- the labor expenditure of individual types of maintenance and the length of performing them;
- the time required for replacement of basic assemblies and apparatus;
- the degree of interchangeability of assemblies and apparatus;
- expenditures for spare parts during maintenance and repair;
- a list of the assemblies and apparatus subject to periodic inspection during operation with and without disassembly from the aircraft;
- the required checking and control equipment.

During the stages of testing a new type of aircraft, the enumerated initial data are selected on the basis of materials of the design offices and are of a temporary nature. A number of indicators for calculation are assumed at the given stage.

The stage of testing and finishing the first models of aircraft is the most important for checking and assessing their maintainability. The future fate of the aircraft and future operating expenses depend to a great extent on the volume and extent of the investigations carried out at the given stage.

However, everything cannot be taken into account at this stage of work. Additional factors, which must be taken into account when assessing maintainability, appear at the beginning of regular operation of the aircraft. During the operational stages, the indicators are calculated by using statistical data obtained from the operation of civil aviation enterprises.

When processing the statistical data obtained, it should be kept in mind that the desired quantitative characteristics depend to a great extent on the means and methods of finding failures and malfunctions, employed in maintenance and repair, the fitting out with control and checking equipment and its quality, the qualifications of the service personnel, etc. Therefore, the data required for calculation of the indicators of maintainability must be obtained from a large number of enterprises with different production conditions. Only in these cases will the data obtained reflect the real activity and may be considered averaged.

When conducting special experiments to obtain the characteristics of maintainability, average conditions must be developed /111
which correspond to real operation. This concerns the service personnel, the control and checking equipment, different devices for repair, lighting,temperature conditions etc. If these conditions are not fulfilled, the reliability of the results obtained will be inadequate. The extent of testing is determined by the required reliability of assessing maintainability. It is usually assumed that data on 50 failures is adequate [17].

2. Determination of the Stability of Processes and Characteristics

The problem of the stability of processes and characteristics is very important in the calculation and assessment of maintainability.

Let us consider one special case which will make it possible to understand the difference between stable stochastic and transient processes. Let the operation on development of repair of a complex machine of a newer type, for example, be performed at several repair plants. The time required for a single repair is random, and at the same time there is every basis to assume that the length of the first repair will be greater on the average throughout all the plants than the similar length of repair of a machine of the same type at those same plants, assuming a sufficiently long period of time after the beginning of development. By this time the random process becomes, as they say, stable or close to stable. Physically, this means that, beginning at some moment of time, the changes in the characteristics of maintainability, in particular, in the average time required for repair of the machine under consideration, cease to depend on the moment of time at which the steady process is considered.

A stricter definition of the concept of stability may be given by using the correlation function between random values. However, a no less strict definition of the stability of a random process may be given by using the function of maintainability (23).

A stochastic process is called stable [6], if the following relation is fulfilled

$$P\{W_t \leq Z\} = P\{W_{t+\alpha} \leq Z\}, \tag{45}$$

where W_t is the random value W_i, considered at moment t.

If we assume $\alpha=-t$, from expression (45), we obtain

$$P\{W_t \leq Z\} = P\{W_0 \leq Z\}.$$

In other words, if the function of maintainability ceases to depend on the considered moment of time t and is determined only by the value Z, the random process is stable. Let $S_n = S_n' + S_n''$ be an alternating renewal process [12], developing in time. The role of alternatives in this process is fulfilled by subprocesses S_n' and S_n''. In other words, the process is now regenerated through random time x_i+w_i and, consequently, we assume the additivity of the renewal and accumulation processes. /112

Alternating processes make it possible to determine in general form the probability $\pi_x(t)$ that operation x_i will be performed at an arbitrary moment of time

$$\pi_x(t) = F_x(t) + \int_0^t \omega_w(u) F_x(t-u)\,du. \tag{46}$$

Stable probability π_x is calculated from equation (46) with the aid of a Laplace transformation and by then performing the limiting transition of the argument:

$$\pi_x = \lim_{t\to\infty} \pi_x(t) = \frac{T_x}{T_x + T_w}. \tag{47}$$

We note that here $T_x+T_w=M(X_i+W_i)$.

In precisely this same way for the probability $\pi_w(t)$ of performing operation W_i at moment $t \to \infty$, we find

$$\pi_w = \lim_{t \to \infty} \pi_w(t) = \frac{T_w}{T_x + T_w} = 1 - \pi_x. \tag{48}$$

Formulas (47) and (48) yield the stable probabilities of performing operations of type X and W, respectively, and considerably simplify the calculations of local characteristics.

Examples.

1. Let T_x be the expenditures for finishing and preparatory operations and let T_w be expenditures strictly for repair or checking of the efficiency of a system. Then the term $\pi_w = 1 - \frac{T_x}{T_x + T_w}$ denotes the fraction of expenditures for "pure" repair within the given volume of finishing and preparatory operations and may be evaluated as the coefficient of accessibility for the subsystem installed in the system.

2. Let T_w be the cost of the ground equipment, at the disposal of the repair shop, suitable for use in maintenance of a new type of machine and let T_x be the cost of lacking equipment. Then $\pi_w = 1 - \frac{T_x}{T_x + T_w}$ is the coefficient of continuity of the ground equipment.

It should be noted that unstable processes and their characteristics are also very important and should be studied, but they are not considered in the given investigation.

3. Calculation of Operative Indicators /11

As already noted, the operative indicators of aircraft maintainability include:

- specific idle times during maintenance and repair K_{mr};
- the average time required for correcting failures during the maintenance cycle $\bar{t}_y$;
- the intensity of recovery μ;
- the probability of correcting the failure within given time t_d of the aircraft idle time $P\{\tau \le t_d\}$.

Specific idle times K_{mr} are calculated by the formula

$$K_{mr} = \frac{P_o + P_p + t_p}{M_c} + \frac{t_{CM}\beta}{M_e(1 - K_{ec})}, \qquad (49)$$

where P_o and P_p are the total idle times in all types of operative and routine maintenance, respectively, during the aircraft repair cycle M_c, in hours; t_p is the idle time of the aircraft during major overhaul in hours; t_{CM} is the average time of the aircraft during replacement of the engine, in hours; β is the coefficient which takes into account the number of engine replacements on aircraft which do not coincide in time of performance with routine types of maintenance; M_e is the repair cycle operating life of the engine, in hours of accrued flight time; and K_{ec} is the coefficient of engine replacement ahead of schedule.

Total idle times P_o and P_p are calculated in turn on the basis of the types of maintenance used for each type of aircraft, the frequency of performing it and the average values of aircraft idle times during each of the types of maintenance.

With respect to the presently existing maintenance regulations and operating conditions for most types of aircraft with gas turbine engines, the approximate analytical expressions for calculating P_o and P_p have the following form:

$$P_o = t_{p.p}\left(\frac{M_c}{3D_n} - N_p\right) + t_{pr.p}\,\frac{M_c}{3D_n} + t_{K.C}\,\frac{2M_c}{3D_n}, \tag{50}$$

$$P_p = t_{3600} + 4t_{1200} + 4t_{600} + 20t_{200} + 90t_{50}, \tag{51}$$

where $t_{p.p}$, $t_{pr.p}$ and $t_{K.C}$ are the average values of aircraft idle times during performance of operative types of maintenance: postflight, preflight and during brief idle periods, respectively, in hours; N_p is the total number of periodic types of maintenance during M_c; D_r is the average length of non-stop flight of the aircraft, in hours; and t_{50}, t_{200}, t_{600}, t_{1200} and t_{3600} are the average values of aircraft idle times during performance of routine types of maintenance every 50, 200, 600, 1200 and 3600 hours of accrued flight time, respectively, in hours.

In the given analytical expression (50) for P_o, the number /11
of operative types of maintenance: postflight — $\left(\frac{M_c}{3D_n} - N_p\right)$, preflight — $\frac{M_c}{3D_n}$ and during brief idle times — $\frac{2M_c}{3D_n}$, is calculated from the quantitative ratio between them, developed in practice. The number of routine types of maintenance in expression (51) for P_p is determined by the calculation method.

Example. In one of the operational enterprises an arbitrary aircraft of type A is found with the following parameters:

- repair cycle operating time of the aircraft M_c=6,000 hours;
- repair cycle operating time of the engine M_e=2,000 hours;
- the average length of non-stop flight D_n=2 hours;
- the coefficient of engine replacement ahead of schedule K_{ec}=0.05;
- the average idle time of the aircraft during major overhaul T_p=960 hours;

- the average idle time during engine replacement t_{CM}=20 hours; β=1;
- the average idle time during preflight maintenance $t_{pr.p}$=1.5 hours;
- the average idle time during postflight maintenance $t_{p.p}$=2.5 hours;
- the average idle time during brief idle periods $t_{K.C}$= 0.75 hours.

The structure of the aircraft repair cycle, the number of routine types of maintenance and the average values of idle times in performing each of them are characterized by the following data (Table 20).

TABLE 20.

Type of routine preventive maintenance	Number of maintenances during M_c	Idle time, hrs.	
		During one maintenance	Total during M_c
Form 1 - every 50 hrs. of aft	90	6	540
Form 2 - every 200 hrs. of aft	20	35	700
Form 3 - every 600 hrs. of aft	5	75	375
Form 4 - every 1200 hrs. of aft	3	105	315
Form 5 - every 3600 hrs. of aft	1	480	480
Total	N_p=119		P_p=2410

It is required to calculate the value of K_{mr} for a given aircraft.

Substituting the corresponding values into expression (50), we obtain

$$P_o = 2.5\left(\frac{6000}{3\cdot 2} - 119\right) + 1.5\frac{6000}{3\cdot 2} + 0.75\frac{2\cdot 6000}{3\cdot 2} = 5200 \text{ hrs.}$$

Using formula (49), we have

$$K_{mr} = \frac{5200 + 2410 + 960}{6000} + \frac{20}{2000\,(1 - 0.05)} = 1.44 \quad \frac{\text{hrs.}}{\text{hrs. of AFT}}.$$

<u>The average time required for correction of failures</u> $\bar{t}_y$ is one of the most important operative indicators of maintainability.

The basis of calculating the average time required for correcting failures is the expression which links the average value of the random value to the value of its possible realizations and the probabilities of the appearance of these realizations. For $\bar{t}_y$ this expression may be written in the form /115

$$\bar{t}_y = \sum_{i=1}^{N} q_i \bar{t}_{yi}, \tag{52}$$

where q_i is the conditional probability of failure of components of the i-th group (of the aircraft system); $\bar{t}_{yi}$ is the average time required for correcting the failure of a component of the i-th group, including the time for detecting it; and N is the number of groups of components in the aircraft.

The conditional probability of failure of components of the i-th group in the general case may be found from the expression

$$q_i = \frac{\omega_i}{\sum_{i=1}^{N} \omega_i},$$

where ω_i is the failure rate of components of the i-th group.

The average time required for correcting failures of components of each of the groups of the aircraft is determined on the basis of the results of statistical processing of the data obtained from practice.

The following should be noted here. The time required for correction of a failure consists of two terms: the time required for detection of the failure and the time required for repair. Calculation of the repair time may be carried out by analysis of all the necessary elementary operations from which the repair process is made up, such as loosening of screws and nuts, soldering of elements, measurement of parameters, removal and installation of individual units, reading of values from the instrument dial, etc.

As statistical data are accumulated, the time intervals required for performing the elementary operations may be known with high accuracy for different specialists.

As an example, the time intervals in seconds, required for performing certain repair operations, are presented below.

Loosening or tightening of a screw with a lock nut	10-20
Loosening or tightening of a screw with a non-locking nut	15-25
Loosening or tightening of a bolt with a lock nut and using ordinary wrenches	30-50
Loosening or tightening of a bolt with a non-locking nut	40-60
Loosening or tightening of screws and bolts, located in poorly accessible places	180-300
Soldering of suspended resistors and capacitors	180-240
Soldering of wire to a lobe	40-60

Calculation of the repair time by the method of operational analysis is especially convenient in cases when repair is performed by replacement of the failed components. /11

More complicated is the problem of determination of the average time required for detection (finding) of the failure.

Finding of failures on civil aviation aircraft is carried out in most cases while observing the following conditions. All operations are performed by personnel who are familiar with the aircraft structure and its systems, who have practical operational experience and who have available the necessary technological equipment. Failures are found by the so-called "manual" method, i.e., by checking of components, units, and parts using the simplest means of inspection.

The process of finding failures is a control process, and the values of its parameters (length, labor expenditure of operations, and the required number of checks) depend on the engineering solutions employed from the list of required checks and the order of performing them.

In each specific case it is recommended that the checking procedure begin on the basis of the developed situation:

- the failure is detected during maintenance, the completion period of which is not rigidly limited;
- the failure occurred immediately prior to takeoff and a delay of the flight is unavoidable;
- the failure was detected during preparation of the aircraft for flight and there is still some reserve time until the takeoff deadline.

For the first situation the optimum control should correspond to the criterion of the minimum average time of finding the failure. for the second — the minimax of time, and for the third — optimum control should provide the most efficient use of the spare time not only for the search, but for performing the required repair before the takeoff deadline according to schedule.

The structure of the typical process of finding a failure in a complex aircraft system is presented in Table 21. For the simpler cases, performance of the individual steps and stages of the search, indicated in the table, may be unnecessary.

There are characteristic features during operation which occur in the behavior of the system upon failure of the i-th component. Using the structure of the typical search process, corrected for each specific case, we can determine the average time required for detecting the failure.

The process of searching for the failure of i-th component may also be simulated on an electronic computer for the purpose of determining its main characteristics.

Thus, after calculation of values q_i and $\bar{t}_{yi}$, the average time required for correction of the failure for the aircraft as a whole, and also for the individual systems $\bar{t}_y$, calculated by formula (52).

The proposed method of calculating $\bar{t}_y$ is comparatively cumbersome, especially with a large number of groups of components in the aircraft. But it is essentially the only one possible /118
under conditions when there is an insufficient amount of statistical data.

TABLE 21.

Formation of the hypotheses about the possible causes of failure	Construction of a diagnostic model for the investigated component	Analysis of the hypotheses and compilation of a program for finding the failure	Determination and correction of the failure
Analysis of the diagnostic features of manifestation of the failure	Determination of controllable parameters	Determination of the conditional probabilities of component failures	Sequential performance of checks
Analysis of the structural and functional diagram of the component	Analysis of the adaptability of the component to performance of checks	Determination of time expenditures for checking the hypotheses	Analysis of the results of checks
Study of the operational characteristics	Designation of the diagnostic elements	Determination of the criterion of optimality and selection of the checking procedure	Correction of the checking program
Classification of the hypotheses about the causes of failure	Construction of a model and selection of methods of checking the components	Designation of the checking sequence	Determination and correction of the failure of the component

In those cases when the required statistical data are sufficient and the nature of the distribution of the time required for routine repair of the given type of aircraft of its individual systems is known beforehand, the average time required for correcting the failure $\bar{t}_y$ is calculated as follows.

With exponential distribution

$$\bar{t}_y = \frac{1}{n}\sum_{i=1}^{n} t_{yi},$$

where n is the number of failures corrected during the maintenance cycle and t_{yi} is the time required for correcting i-th failure.

With logarithmic normal distribution

$$\lg \bar{t}_y = \bar{x} + 1.1513\sigma_x^2,$$

where $\bar{x} = \frac{1}{n}\sum_{i=1}^{n} \lg t_{yi}$ is the mean statistical normal distribution;

and $\sigma_x^2 = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2}$ is the variance of x.

As can be seen from the foregoing, calculation of the average time required for correction of failure $\bar{t}_y$ in such a manner is very simple, but requires a large amount of statistical data. Moreover, its use in production stages is possible only for those machines in which the same methods of design and manufacture will be used as in a machine about which the data on t_y was gathered.

The rate of correction of failures (routine repair) is calculated as the value, inverse to the average time required for correction of the failure $\bar{t}_y$

$$\mu = \frac{1}{\bar{t}_y}.$$

The probability of correcting a failure during given time t_d $P_y\{\tau \le t_d\}$ is calculated as a function of the probability distribution of the time of routine repair. The time distribution of routine repair is calculated mainly by the usual method of detecting the failed element and by the characteristics of the design of the aircraft system.

If the aircraft systems and their components are of the modular type, and repair is accomplished by the replacement method, then there is usually an exponential distribution of the routine repair time. This distribution is also valid for relatively /11
simple apparatus, for example, for a radio receiver.

In the case of exponential distribution

$$P_y\{\tau \le t_d\} = 1 - e^{-\mu t_d},$$

where μ is the rate of routine repair, and t_d is the given time of aircraft idle time.

The exponential distribution is manifested more clearly during routine repair of electronic digital computers, detection of failures of which is carried out with the aid of test programs. Thus, it was established as a result of processing statistical data on restoration of one of the machines that agreement of the hypothesis of exponential distribution of the routine repair time with the statistical data comprises 0.3-0.5 according to the χ^2 criterion (the average time required for correcting the failure is 3-5 hours). The integral curves of the probability of the routine repair time of a machine are presented in Figure 48: 1- theoretical curve and 2- statistical curve [17].

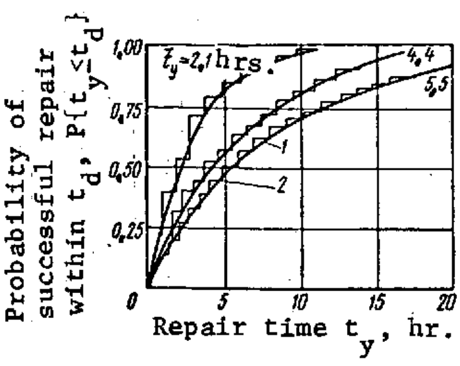


Figure 48. Probability curves of routine repair time of an electronic digital computer.

In a number of cases when detection of failures is carried out manually, the distribution of routine repair time differs from the exponential distribution.

The logarithmic normal distribution is more common in practice, for which $P\{\tau \le t_d\}$ is expressed in the following manner:

$$P_y\{\tau \le t_d\} = \int_0^{t_d} q_y(\tau) d_\tau,$$

where $q_y(\tau)$ is the probability density of routine repair time.

The probability curves of the routine repair time of the on board radio station AN/ARS-27 are presented in Figure 49; 1- theoretical curve with a logarithmical normal distribution and 2- statistical curve, obtained as a result of processing the data on 232 repairs of the station [19]. Figure 49 indicates the rather close agreement of the statistical and theoretical curves.

The routine repair time is distributed according to Erlange's law for some components of electronic apparatus without automatic search for failures [17]. In the given case the value of $P_y\{\tau \le t_d\}$ is calculated as follows:

$$P_y\{\tau \le t_d\} = 1-(1+2\mu t_d)e^{-2\mu t_d}.$$

/120

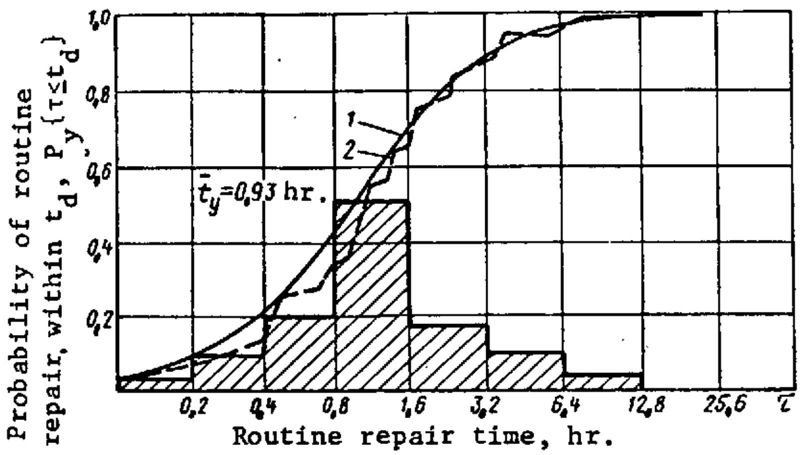


Figure 49. Probability curves of the routine repair time for station AN/ARS-27.

Example. Let us assume that, as a result of processing statistical data on the time required for correction of failures of the components of one of the aircraft systems, we obtained $\bar{t}_y$=40 minutes. The rate of correcting the failures is accordingly equal to μ=0.025.

It is required to calculate the probability of correcting the failure of the system within given time t_d, equal to 60 minutes, for cases of exponential distribution of routine repair time and the Erlange distribution.

In the case of the exponential distribution we have

$$P_y\{\tau \leqslant t_d\} = 1 - e^{-\mu t_d} = 0{,}777.$$

In the case of the Erlange distribution

$$P_y\{\tau \leqslant t_d\} = 1 - (1 + 2\mu t_d)e^{-2\mu t_d} = 0{,}801.$$

4. Calculation of the Economic Indicators

The economic indicators of maintainability include:
- the specific labor expenditures in routine maintenance and repair K_T, man-hours/hours of accrued flight time;
- the specific expenditures for materials and spare parts K_{sp}, rubles/hours of accrued flight time;
- the probability of successful performance of routine repair with limited labor resources $P\{T \leq T_d\}$ or with limited reserves of spare parts $P\{S \leq S_d\}$.

<u>Specific labor expenditures</u> K_T are calculated by the formula

$$\frac{(T_{C.M}+T_{p.e})n_e}{M_e(1-K_{ec})} \tag{53}$$

where ΣT_o is the total labor expenditures for performing all types /121 of routine maintenance, including operations to correct the failures and malfunctions during the repair cycle operating life of the aircraft M_c, man-hours; $T_{p.c}$, $T_{p.e}$ and T_{ai} are the labor expenditures for major overhaul of the aircraft, engine, and apparatus, respectively, man-hours; T_{CM} is the labor expenditures for replacement of the engine, man-hours; M_e and M_{ai} are the repair cycle operating times of the engine and apparatus, respectively, hours of accrued flight time; K_{ec} and K_{ai} are the coefficients of engine and apparatus replacements ahead of schedule, respectively; n_e and n_i are the number of engines and apparatus of each type, respectively, on the aircraft; and N_a is the number of types of apparatus, replaced on the aircraft at intervals M_c.

The total labor expenditures ΣT_o are in turn calculated on the basis of the types of routine maintenance of the aircraft used within the limits of M_c and of the average values of the labor expenditures for performing each of the types of maintenance.

The analytical expression for ΣT_o may be written with respect to the existing maintenance regulations for most types of gas-turbine aircraft in the following manner:

$$\Sigma T_o = \sum_{i=1}^{k} T_i n_i + T_{pr.p} \frac{M_c}{SD_n} + T_{K.C} \frac{2M_c}{SD_n} + T_{p.p} \frac{M}{SD_n} - \sum_{l=1}^{y} n_i + \sum_{i=j}^{m} T_j . \quad (54)$$

where T_i is the labor expenditure of the i-th form of routine maintenance, man-hours; n_i is the number of routine maintenances of i-th form, performed during M_c; k is the number of different forms of routine maintenance, used for the aircraft; $T_{p.p}$, $T_{pr.p}$ and $T_{K.C}$ are the average values of labor expenditures to perform the operative types of maintenance — postflight, preflight and during short idle periods, respectively, man-hours; T_j are the labor expenditures for performing the j-th modification of the aircraft design according to reports, man-hours, and m is the number of modifications performed during M_c.

The number of operative types of maintenance is determined in analytical expression (54) in the same manner as in expression (50) when calculating the total idle times P_o.

Example. The value of specific labor expenditures for maintenance and repair K_T must be calculated for one of the arbitrary aircraft of type a. The aircraft is characterized by the following parameters:

- the repair cycle operating time of the aircraft M_c=6,000 hours;

- the repair cycle operating time of the engine M_e=2,000 hours;
- the number of engines on the aircraft n_e=4;
- the average length of non-stop flight D_n=2 hours;
- the coefficient of engine replacement ahead of schedule K_{ec}=0.05;
- the average values of labor expenditures in major overhaul of the aircraft $T_{p.c}$=30,000, and in major overhaul of the engine $T_{p.e}$=2,000 man-hours;
- the average labor expenditure of engine replacement T_{CM}= 200 man-hours; /122
- the average values of labor expenditures to perform post-flight manntenance $T_{p.p}$=15, preflight $T_{pr.p}$=10, and during brief idle periods $T_{K.C}$=8 man-hours;
- the labor expenditures of performing modifications on the aircraft during the repair cycle operating lifetime $\sum_{j=1}^{m} T_j=600$ man-hours.

The number of periodic types of preventive maintenance during M_c and the average expenditures in performing each of them are characterized by the data of Table 22.

TABLE 22.

Type of routine maintenance	Number of maintenances during M_c	Labor expenditures, man-hrs.	
		Per maintenance	Total during M_c
Form 1 every 50 hr. of aft	90	40	3600
Form 2 every 200 hr. of aft	20	350	7000
Form 3 every 600 hr. of aft	5	500	2500
Form 4 every 1200 hr. of aft	3	900	2700
Form 5 every 3600 hr. of aft	1	6000	6000
Total	N_p=119		21800

The parameters of the apparatus of the aircraft systems, having an operating lifetime before overhaul of less than the operating time of the airframe, have the following values (Table 23). Arbitrary data are presented as an example only for several apparatus in the table.

TABLE 23.

Name of apparatus	Type, code	M_{ai}, μ	n_i, units	K_{ai}	T_{ai}, man-hr
Assembled brake wheel	KT 81/3	2,000	8	0.015	14.9
Hydraulic pump	NP 25/5	3,000	2	0.12	9.6
Air pressure regulator	469D	3,000	2	0.007	14.0
Sliding valve	438B	3,000	2	0.05	4.7
Temperature regulator	1074	2,000	4	0.09	5.0

Having similar data for all N types of apparatus, installed on the aircraft, according to the expression presented in formula (53),

$$\sum_{i=1}^{N_a} \frac{T_{ai} n_i}{M_{ai}(1-K_{ai})}$$

we calculate the specific labor expenditures for repair of the apparatus.

Let us assume that in the given example the specific labor expenditures for repair of apparatus comprise 0.5 man-hour per hour of accrued flight time.

Substituting the appropriate values in expression (54), we obtain

$$T_0 = 21\,800 + 10\frac{6000}{3.2} + 8\frac{2\cdot 6000}{3.2} + 15\left(\frac{6000}{3.2} - 120\right) + 600 = 61\,600 \quad \text{man-hr.}$$

Using formula (53), we have

$$K_{\text{т}} = \frac{61\,600 + 30\,000}{6000} + \frac{(200 + 2000)\,4}{2000\,(1 - 0{,}05)} + 0{,}5 = 20{,}38 \text{ man-hr per hr of AFT}$$

<u>The specific expenditures for materials and spare parts</u> K_{sp} are calculated by the formula

$$K_{sp} = \frac{C_o + C_p}{M_c} + \frac{C_e n_e}{M_e\,(1 - K_{ec})} + \sum_{i=1}^{N} \frac{C_{ai} n_{ai}}{M_{ai}(1 - K_{ai})}$$

where C_o is the total expenditures for spare parts during performance of all types of preventive maintenance during M_c, in rubles. The components of total expenditures for spare parts and the method of calculating C_o are similar to that used in formula (53) for T_o; C_p, C_e and C_{ai} are the expenditures for spare parts during major overhaul of the aircraft, engine and the i-th apparatus, respectively, in rubles.

The method of calculating indicator K_{sp} does not essentially differ in any way from the method described earlier for calculation of specific labor expenditures K_T.

It should be noted that in recent years some foreign firms and airline companies calculate indicators K_T and K_{sp} not only for the aircraft as a whole, but for its individual systems as well. This considerably facilitates analysis and determination of the operating lifetimes for improving the indicators of specific labor expenditures and expenditures for spare parts.

The calculated values of K_{sp} for the individual systems of the BAC-111 aircraft during operation over a range of 400-500 km according to the situation for 1969 are presented in Table 24. The systems are enumerated according to the specifications of ATA-100 (the United States Air Transport Association).

TABLE 24.

Number of system according to ATA-100	Nomenclature of system	Values of K_{sp}, pounds sterling per hour of accrued flight time
21	Air conditioning system	0.297
22	Automatic pilot	1.012
23	Communications facilities	0.251
24	Electric power sources	0.403
26	Fire-prevention equipment	0.016
27	Aircraft control system	0.985
28	Fuel system	0.098
29	Hydraulic system	0.478
30	Anti-icing system	0.143
31	Instruments	0.012
32	Landing gear	1.521
33	Lighting	0.048
34	Air navigation equipment	0.518
35	Oxygen equipment	0.019
36	Air conditioning equipment	0.202
38	Water system	0.103
49	Auxiliary power plant	0.496
52	Doors	0.039
73	Fuel supply	0.062
75	Engine air system	0.116
77	Engine operation monitoring instruments	0.071
79	Oil system	0.0004
80	Ignition system	0.042
	Total	6.937
	Variation 25%	1.734

The total for the aircraft airframe and its system K_{sp}=8.671. The calculated value of indicator K_{sp} for the Rolls Royce Spey 511 engines comprises 10.18 pounds sterling per hour of accrued flight time. The total for the BAC-111 aircraft K_{sp}=18.851.

Along with the economically determined indicators of maintainability K_T and K_{sp}, in a number of cases it is necessary to calculate the probabilistic economic indicators.

The probability of successful performance of routine repair with limited labor resources $P\{T_{T.P} \leq T_d\}$ is calculated on the basis /124 of the nature of the distribution of labor resources for routine repair of the aircraft during the maintenance cycle.

The average empirical value of labor expenditures for routine repair during the maintenance cycle $\overline{T}_{T.P}$ may be presented in the form

$$\overline{T}_{\text{т.р}} = \frac{1}{n} \sum_{i=1}^{n} T_{\text{т.р}\,i},$$

where n is the number of failures during the maintenance cycle; $T_{T.Pi}$ is the labor expenditure of correcting the i-th failure.

The probability of successful completion of routine repair with T_d for the exponential distribution of $T_{T.P}$ is calculated from the expression

$$P\{T_{\text{т.р}} \leqslant T_d\} = 1 - e^{-\frac{T_d}{\overline{T}_{\text{т.р}}}}.$$

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The probability of successful completion of routine repair with limited reserves of spare parts $P\{S_{T.P} \leq S_d\}$ is calculated similarly to the preceding indicator.

With exponential distribution of random value $S_{T.P}$

$$P\{S_{T.P} \leq S_d\} = 1 - e^{-\frac{S_d}{\overline{S}_{T.P}}}, \qquad (55)$$

where S_d is the given level of spare parts reserves; and $\overline{S}_{T.P}$ is the average value of expenditure of spare parts.

Example. Aircraft of type A, based in one of the large airports, perform regular flights to a number of other airports.

All types of routine maintenance, replacements of apparatus according to completion of the operating life and major overhaul of the aircraft are carried out at the home airport, where the main warehouse of spare parts and materials is located.

Only operative types of maintenance and routine repair, related to correction of sudden failures of apparatus and finished components, are carried out on the aircraft at all airports. There are no large warehouses of spare parts at these airports; there are only limited reserves of some apparatus, components and finished articles.

Let us assume that these reserves at i-th airport comprise $S_d=14$ units for one of the finished articles; the average value of expenditure of a given finished article $S_{T.P}=8$ units.

It is required to calculate the probability of successful completion of routine repair of aircraft at i-th airport in case of failures of a given finished article, if it is known that the value of $S_{T.P}$ is distributed exponentially.

From expression (55), we find

$$P\{S_{T.P} \leq S_d\} = 1 - e^{-\frac{14}{8}} = 1 - e^{-1,75} = 0,826.$$

Separate calculations are carried out in a similar manner for each of the nomenclatures of apparatus and finished articles which have sudden failures away from the home airport, and which are subject to rapid correction.

The probability of successful completion of routine repair for the aircraft as a whole is calculated by multiplication of the probabilities obtained for each of the apparatus.

5. Calculation of Supplementary Indicators

This group of indicators, as pointed out, is used to evaluate the individual properties of an aircraft design, which determine the maintainability and which directly affect the level of maintainability.

Each of the supplementary indicators is calculated with the aid of a simple formula. These formulas for stable operating conditions were obtained at the beginning of the present chapter and are presented in general form in expression (47) and (48).

The supplementary indicators are expressed in the form of dimensionless coefficients, which vary within the range from /126
0 to 1. It is assumed that the design corresponds completely to the requirements placed on it with respect to one or another of its properties, if the coefficient characterizing this property is equal or close to 1.

Accessibility to an object of maintenance and repair is calculated by the coefficient of accessibility K_a, calculated by formula

$$K_a = 1 - \frac{T_{add}}{T_{add} + T_b}, \tag{56}$$

where T_{add} is the labor expenditure of additional operations, man-hours; and T_b is the labor expenditure of performing the basic purposeful operation, man-hours.

In the given case additional operations include those such as removal and installation of all types of hatch covers, panels, cowlings, fillets, heat and sound installation, disassembly and assembly of installed equipment and equipment not subject to removal etc.

C-3

The basis of purposeful operations are checking, regulating, lubrication and recharging operations, disassembly and assembly of apparatus and finished articles subject to replacement, etc.

The coefficients of accessibility may be calculated for individual apparatus, systems and for the aircraft as a whole.

Example. The labor expenditures for replacement of the PNV-2 fuel pump on one of the aircraft comprise 1.5 man-hours, of which 0.9 man-hour is expended for additional operations on removal of the hatch cover and 0.6 man-hour is expended directly on removal and installation of the pump. It is necessary to calculate the value of the coefficient of accessibility for the given apparatus.

From expression (56), we have $K_{a.a}=1-\frac{0.9}{1.5}=0.4$.

The coefficients of accessibility for all other apparatus of the system may be calculated in a similar manner.

Having available the data for the individual apparatus, we can easily calculate the values of $K_{a.c}$ for the system as a whole. For this purpose the required information on the apparatus is outlined in the appropriate form (Table 25), suitable for calculation of the values required in calculation of $K_{a.c}$.

According to equation (56), we obtain

$$K_{a.c}=1-\frac{\Sigma T_{add}}{\Sigma T_{day}} = 1 - \frac{3.5}{6.6} = 0.47$$

The ease of disassembly of the components of an aircraft structure and of its systems is calculated by the coefficient of ease of disassembly K_d, calculated by the formula /12

TABLE 25.*

Nomenclature of assembly	T_{add}, man-hr	T_b, man-hr	T_{day}, man-hr	$T_{a.a}$
Assembly № 1	0,9	0,6	1,5	0,4
» № 2	0,2	0,4	0,6	0,67
» № 3	0,3	0,5	0,8	0,63
» № 4	0,8	0,4	1,2	0,34
» № 5	1,3	1,2	2,5	0,48
Total	3,5	3,1	6,6	

*Translator's note: Commas in numbers represent decimal points.

$$K_d = 1 - \frac{\Delta T_{a.m}}{T_{a.m}}, \tag{57}$$

where $T_{a.m}$ is the labor expenditure of disassembly and assembly operations of the component (system) under consideration, man-hours; $\Delta T_{a.m}$ is the excess labor expenditure of disassembly and assembly operations on the component (system) being considered compared to the standard value, in man-hours.

Indicators of the ease of disassembly, given in the specifications, or of a similar model of the component (system), taken as a standard, are used as standard values in the given case.

Example. A total of 2.5 man-hours is expended to perform the operations of disassembly and assembly of the wheel of one of the aircraft. On another type of aircraft, taken as the standard for the given operation, the labor expenditures for disassembly and assembly of the wheel comprise 2.0 man-hours. It is required to calculate the coefficient of ease of disassembly of the wheel.

From equation (57), we obtain

$$K_d = 1 - \frac{2,5 - 2,0}{2,5} = 0,8.$$

The interchangeability of a structural component is calculated by the coefficient of interchangeability K_i. The given coefficient is calculated by the following formula:

$$K_i = 1 - \frac{T_a}{T_a + T_{a.m}}$$

where T_a is the labor expenditure of adjusting, checking or tuning operations in replacement of the component, man-hours; and $T_{a.m}$ is the labor expenditure of disassembly and assembly operations on the component under consideration, man-hours.

When calculating K_i, all types of adjusting, checking or tuning operations, performed at the point of installation on the aircraft of a new assembly, apparatus or unit or one taken from a rotating stock, are included in the value of T_a. The checking and adjusting operations are usually performed on the components of electrical, radial and instrument equipment of the aircraft.

The checkability of individual systems and of the aircraft as a whole is calculated by the coefficient of checkability K_K, calculated by the formula

$$K_K = 1 - \frac{\sum_{j=1}^{m} T_j K_j}{\sum_{i=1}^{n} T_i K_i + \sum_{j=1}^{m} T_j K_j}$$

where T_i is the labor expenditure of one-time checking of the technical condition of the i-th component, not requiring disassembly from the aircraft, in man-hours; T_j is the labor expenditure of one-time checking of the technical condition of the j-th component, requiring disassembly from the aircraft, including the /128 labor expenditure of its disassembly and assembly, man-hours; and m and n are the numbers of the components in the system (on the aircraft), which require and do not require disassembly for checking of their technical condition, respectively; and K_i and K_j are the frequencies of checking the components during the repair cycle operating life of the aircraft M_c, not requiring and requiring disassembly, respectively.

Unlike the preceding coefficients, the coefficient of checkability may be determined immediately for individual systems and for the aircraft as a whole.

The continuity of ground equipment facilities for maintenance and repair of aircraft is calculated by the coefficient of continuity K_c.

The recommended formula for calculation of K_c in the general case has the following form:

$$K_c = 1 - \frac{C_{n.o}}{C_{n.o}+C_{c.o}} \tag{58}$$

where $C_{n.o}$ is the cost of a set of new equipment (control and checking, repair etc.), intended for preventive maintenance and repair of an aircraft only of a given type, in thousands of rubles; and $C_{c.o}$ is the cost of a set of serially produced equipment, already in use, in thousands of rubles.

In order to calculate K_c by formula (58), it is necessary to have data not only on the nomenclature of the ground equipment, required for maintenance and repair of an aircraft, but also on the cost of each item.

In practice the coefficient of continuity is sometimes calculated by a simpler method, namely, by the ratio of the amount of equipment in sets rather than by its cost. The advantage of this method is the comparative simplicity of calculation. However, its accuracy is insufficient in a number of cases.

The coefficient of continuity may also be calculated in a similar manner according to formula (58) for the control and checking apparatus.

The considered additional indicators are not exhaustive. In some cases it may be necessary to use other supplementary indicators (the degree of standardization of components (systems), the degree of standardization of support components, etc.).

The method of calculating them essentially does not differ from that outlined above, i.e., calculation is carried out by using analytical expression (47) and (48).

6. The Task of the Indicators of Maintainability Within the General Requirements on Aviation Materiel /129

In solving the problem of increasing the maintainability of aircraft, the method of the task of indicators in the general technical requirements on aviation materiel occupy an important position, along with calculation of them. In practice the problem of the method of assigning indicators of maintainability in the specifications arises rather frequently. However, there are no recommendations on solution of this problem in the known literature.

Let us consider some aspects of solving this problem for part of the generalized indicators with respect to civil aviation transport aircraft. The essence of the proposed method reduces to the following. First, the values of the considered generalized indicators of maintainability are calculated by the results of processing actual data on maintenance and repair of aircraft of different types, using the methods outlined in the preceding sections. The dependence of the indicators on certain basic characteristics of aircraft, such as, for example, the structural weight, productivity, commercial payload, cost of a new aircraft, annual utilization etc. is found with the aid of correlation regression analysis.

Thus, the indicator of specific labor expenditures in maintenance and repair K_T for the aircraft as a whole, as indicated by practice, may most conveniently be presented as a function of the structural weight of the aircraft G or of its productivity B:

$$K_{\tau}=f(G) \text{ or } K_{\tau}=f(B). \tag{59}$$

The indicator of specific expenditures for materials and spare parts K_{sp} is a function of the cost of a new aircraft C_n

$$K_{sp}=f(C_n). \tag{60}$$

The indicator of specific idle times for preventive maintenance and repair K_{mr} may be presented as a function of the annual utilization of the aircraft W_{aft}

$$K_{mr}=f(W_{aft}). \tag{61}$$

The probability of correcting a failure $P\{\tau\leq t_d\}$ is found as a function of the scheduled idle times of the aircraft between contiguous flights t_d provided that the law of distribution of t_y or $T_{T.P}$ is known:

$$P\{\tau\leq t_d\}=f(t_d). \tag{62}$$

In a number of cases the indicator of the probability of the takeoff of the aircraft being delayed P_d is used instead of indicator $P\{\tau \leq t_d\}$.

In the given case the following function is used /13

$$P_d = f(\mu, \omega), \tag{63}$$

where μ is the intensity of correcting failures; and ω is the failure rate.

Processing of actual data on the labor expenditures for preventive maintenance and repair of different types of transport aircraft showed that specific labor expenditures K_T may be expressed in the form of a linear function of the structural weight of the aircraft G. The specific expenditures for materials and spare parts K_{sp} may also be expressed as a linear function of the cost of a new aircraft C_n.

The specific idle times K_{mr} are expressed as a curvilinear function of the annual utilization W_{aft}. There is also a curvilinear dependence between $P\{\tau \leq t_d\}$ and t_d, and P_d and μ.

The functions obtained in this manner reflect the current situation and may be used primarily for comparative analysis of the level of maintainability of aircraft already developed and in operation.

It is natural to expect a considerable improvement of the indicators of maintainability from new-generation aircraft in order to provide given future rates for reduced operating expenditures and idle times, and for the increasing annual utilization and regularity of flights.

In this regard the functions of the indicators of maintainability of form (59)-(63), obtained as a result of calculation and analysis, for assignment in the specifications for new types of aircraft should be corrected by taking into account the given future rates of variation of such aircraft characteristics as operating expenses, idle times, utilization, regularity and also in the data on the maintainability of the best Soviet and foreign models of machines.

In a number of cases specific doubts may be encountered on the part of individual specialists with respect to the accuracy of the proposed method of calculating the indicators of maintainability for assignment in the specifications for new types of aircraft. In the formal sense they are correct. The proposed method, if it is considered strictly in the mathematical sense, is of course not quite accurate. It may be used only to easily determine the order of figures, but the given method may not be used to confirm that the values of the indicators, derived and recorded in the specifications, should be determined with an accuracy up to hundredths and thousandths of decimal places. However, there is as yet no practical necessity for this.

Precise calculation and extensive justification of the required level of each of the indicators of maintainability for new types of aircraft is an extremely complicated problem, and in a number of cases simply impossible at present. Much time is required for solution of it. It may be that the new generation /131
of machines will be developed sooner than investigations on the basis for their required level of indicators of maintainability are completed.

Moreover, many years of practice shows that the main thing in determination of the level of indicators is not so much the mathematical accuracy of their calculations and the correctness of the justifications (although this is very important), as the correctly ascertained and completely considered tendency in calculations of variation of the indicators and of the main operating characteristics of the aircraft. Therefore, the proposed simplified method of calculating the level of indicators of maintainability for assignment of them in the specifications is now quite justified, rather easy to accomplish and at the same time quite accurate.

Using the given method, for example, we can calculate the level of certain generalized indicators of maintainability for assignment in the specifications for new types of gas-turbine transport aircraft.

It is recommended that the specific labor expenditures K_T be given in the specifications by a linear empirical function of G of the form:

$$K_T = 2.8 + 0.165G,$$

where G is the structural weight of the aircraft in tons.

It is recommended that specific expenditures for materials and spare parts K_{sp} be given as a linear empirical function of C_n of the form:

$$K_{sp} = \frac{0.0095C_n}{1000},$$

where C_n is the cost of a new aircraft, in rubles.

The recommended dependence of specific idle times K_{mr} on the annual utilization of the aircraft W_{aft} in hours of accrued flight time was presented earlier (see Figure 3).

It is obvious from Figure 3 that the components of this indicator — specific idle times for operative $K_{p.o}$ and periodic

$K_{p.p}$ types of maintenance and in repair $K_{p.r}$ — should not in turn exceed the values for given W_{aft} established for them in order to provide the corresponding value of K_{mr} with the given annual utilization of the aircraft.

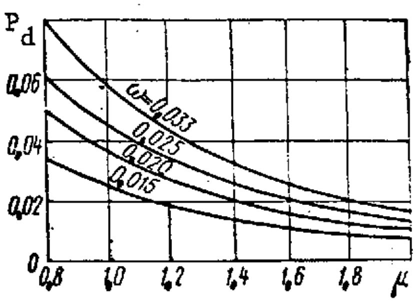

Figure 50. Dependence of the probability of a delay in takeoff P_d on the indicators μ and ω where t_d=1 hour.

The dependence of $K_{p.o}$, $K_{p.p}$ and $K_{p.r}$ on the annual utilization of the aircraft were obtained with consideration of the ratios between idle times for individual types of maintenance and repair, established in practice at civil aviation enterprises. /132

And finally, the empirical dependence of the indicator of the probability of a delay in the takeoff of the aircraft P_d on μ with different values of the failure rate ω of the aircraft ratio equipment is given in Figure 50.

As already noted previously, the given empirical functions are presented with consideration of the prospects for development of aviation materiel and improvement of methods of maintenance of it, and also with consideration of the best advances of foreign firms and airline companies. They may be used as standards.

Similar functions are also used in foreign practice to assign the indicators of maintainability in specifications. Moreover, some indicators are calculated and assigned in specifications separately for the aircraft and engine.

Thus, according to [49], it is recommended that the specific labor expenditures $K_{T.C}$ for a gas turbine aircraft be calculated by the following empirical formula:

$$K_{T.C}=0{,}59\left[0{,}05\frac{G_e}{1000}+6+\left(\frac{630}{\frac{G_e}{1000}+120}\right)\right],$$

where G_e is the weight of an empty aircraft with engines, in pounds.

The specific labor expenditures for engines $K_{T.D}$ are calculated by the formulas:

- for turbojet engines

$$K_{T.D}=\left[0{,}6+\frac{0{,}027T}{1000}\right]n_e,$$

- for turboprop engines

$$K_{T.D}=\left[0{,}65+\frac{0{,}03T}{1000}\right]n_e,$$

where T is the maximum takeoff thrust of the engine, in kg; and /133
n_e is the number of engines on the aircraft.

The specific expenditures for materials and spare parts K_{ea} for a gas turbine engine should be calculated by the formula

$$K_{ea}=3.08C_n\cdot 10^{-6},$$

where C_n is the cost of a new aircraft (with deduction of the cost of the engines), in dollars.

For gas turbine engines, installed on subsonic aircraft, the value of K_{ee} is calculated from the expression

$$K_{ee}=2.5n_eC_e\cdot 10^{-5},$$

where C_e is the cost of a new engine, in dollars.

For engines installed on supersonic aircraft,

$$K_{ee}=4.2n_e C_e \cdot 10^{-5}.$$

The requirements which were at one time placed on the BAC-111 aircraft by the airline companies are of practical interest [27]. In order to reduce the idle times of the aircraft for maintenance and repair, these requirements especially provided the following:

- the time of replacing the components, including their testing and checking after replacement, should not exceed the values given in Figure 51;
- the time required for completing the maintenance operations should not exceed the values given in Figure 52;
- the time expended on checking of the system functioning /134
should not exceed the values given in Figure 53.

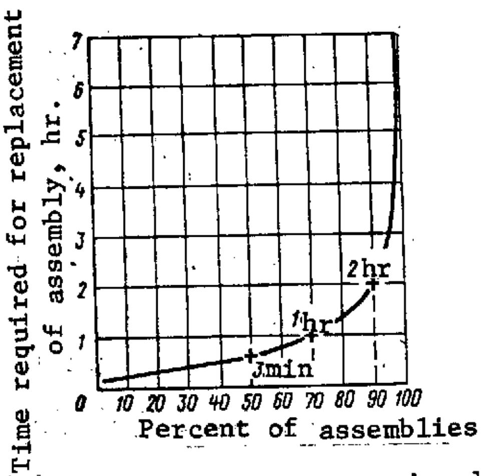

Figure 51. The time required for replacement of the assemblies and units of the BAC-111 aircraft, including their testing and checking.

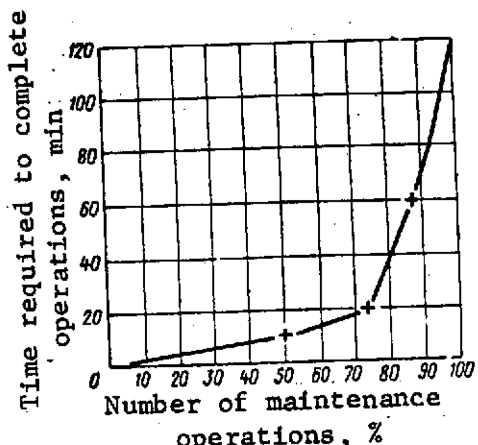

Figure 52. The time required for completing maintenance operations on the BAC-111 aircraft.

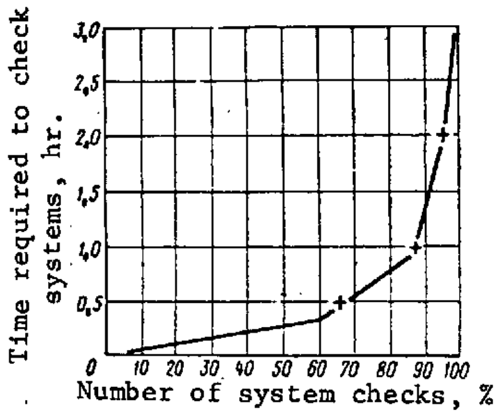

Figure 53. The time required for checking the functioning of systems of the BAC-111 aircraft.

Fulfillment of the enumerated requirements by BAC made it possible to considerably increase the operational readiness of the aircraft fleet, the regularity of flights and to provide an annual accrued flight time for the registered BAC-111 aircraft of 2,500-3,000 hours.

7. Analysis of Aircraft Maintainability

After consideration of the problems of methods of calculating indicators of maintainability and methods of assigning the level of indicators and specifications for new types of aircraft, it is natural to dwell on the problem of analysis of maintainability.

There are as yet no special final procedural developments on problems of analysis of the maintainability of machines. The concept of analysis is identified with calculation of indicators in some of the few published papers on maintainability and repairability. It is assumed in these papers that, having calculated the required indicators, the problem of analysis solves itself.

Moreover, calculation of the indicators and analysis of the level of maintainability are different problems. For example, all the required indicators may be calculated exceptionally accurately, but may not help to solve the problem of analysis of the level of maintainability of the considered type of aircraft.

Analysis is the final stage of investigations and a more complex and responsible stage. Final conclusions about the maintainability of an aircraft are made from the results of completion of the given stage. It follows from this that development of simple and reliable methods of analysis is one of the most important problems.

How can the level of maintainability of one or another type of aircraft be analyzed? We feel that one of the methods outlined in [15] with respect to analysis of the quality of articles may be used to solve this problem.

Using the given method as the basis, the level of maintainability may be analyzed by comparing the quantitative values of the indicators, obtained as a result of calculation for the considered type of aircraft, with the level of the values of indicators, given in the specifications, or of similar models of aircraft (domestic or foreign), taken as the standard. The relationship of the values of the corresponding indicators of the considered and standard aircrafts, expressed by a relative number or in percentage, is taken as the measure of comparison.

In the given case analysis of maintainability is carried out differentially for each of the indicators. The generalized indi- /135
indicators are considered first, and then the special indicators for certain important apparatus and components, stipulated in the specifications, are considered.

The calculating formula for analyzing maintainability by any of the indicators has the form:

$$D_i = \frac{K_{ip}}{K_{is}} 100\%, \tag{64}$$

where D_i is the coefficient of comparative analysis of maintainability by the i-th indicator of the considered and standard aircraft; and K_{ip} and K_{is} are the values of the corresponding compared indicators of the considered and standard aircraft. Performing the calculations by using formula (64), we obtain a number of values of D_1, D_2 and D_3, of which it follows that the level of maintainability of the considered machine according to indicator 1 comprises D_1% of the standard, according to indicator 2 — D_2%, according to indicator 3 — D_3% etc.

The level of maintainability of the considered aircraft according to the generalized indicators K_T, K_{sp} and K_{mr} will be higher than the standard, if for each of them D_i<100%. The level of maintainability of the considered aircraft is below that of the standard aircraft based on indicators for which D_i>100%. A positive analysis is given in those cases when D_i≤100%.

The following conditions occur for generalized probabilistic indicators of type $P\{\tau \le t_d\}$ and for all special indicators. If D_i<100%, the level of maintainability of the considered aircraft is below that of the standard, and if D_i>100%, it is higher. A positive analysis is given in D_i≥100%.

Example. It is required to give a differential analysis of the maintainability of an aircraft of type B according to some generalized and special indicators. The values of these indicators given in the specifications for a given type of aircraft, are taken as standard indicators.

Performing the necessary calculations and obtaining the values of the appropriate indicators for the considered aircraft, let us record them in a table of specific form (Table 26). Let us also write down the results of diffential analysis of aircraft maintainability by each of the indicators, obtained by formula (64)

TABLE 26.

Name of indicators	Dimensionality	Value of indicator: Of the considered aircraft	Value of indicator: Of the standard	D, %
Generalized				
Specific labor expenditures K_T	$\frac{\text{man-hours}}{\text{hours of AFT}}$	13.2	12	110(-)
Specific expenditures for materials and spare parts K_{sp}	$\frac{\text{rubles}}{\text{hr of AFT}}$	24	25	96(+)
Specific idle times K_{mr}	$\frac{\text{hour}}{\text{hr of AFT}}$	0.78	0.8	98(+)
Probability of correcting failure $P\{\tau \leq t_d\}$ within time t_d	—	0.98	0.98	100(+)
Special				
Coefficient of accessibility K_a	—	0.8	0.85	94(-)
Coefficient of ease of disassembly K_d	—	0.9	1.0	90(-)
Coefficient of interchangeability K_i	—	0.92	0.9	102(+)

In the considered example a positive analysis of maintainability may be given by the following indicators: specific expenditures for spare parts K_{sp}, specific idle times K_{mr}, the probability of correcting the failure $P\{\tau \leq t_d\}$ and the coefficient of interchangeability K_i. A negative analysis is obtained for the other indicators. Other design work must be carried out to increase the level of the indicators of accessibility and ease of disassembly of the apparatus to the given values. Solution of this problem makes it possible to considerably improve the indicator of specific labor expenditures K_T.

The differential method of analysis does not usually yield clear solution of the level of aircraft maintainability. If necessary this problem may be resolved by using so-called multiple / indicators.

The multiple indicator is capable of calculating simultaneously the values of all indicators of maintainability. The analytical expression for the multiple indicator A_K has the form:

$$A_K=\frac{1}{n}(a_1D_1+a_2D_2+a_3D_3+\ldots+a_nD_n),$$

where a_1, a_2, a_3, ..., a_n are the "weighting" coefficients which characterize the specific weight of each of the indicators of maintainability in the multiple indicator; D_1, D_2, D_3, ..., D_n are calculated by formula (64); and n is the number of indicators.

The advantages of a method of analysis by the multiple indicator are obvious. Moreover, its practical use is difficult at present due to the extreme complexity of calculating the "weighting" coefficients.

8. Methods of Gathering and Processing of Data on Maintainability

Taking into account the characteristics of data on aircraft maintainability, we can determine the general requirements for this data such as reliability, completeness, uniformity, timeliness and continuity.

Reliability is achieved by the objectivity of the presented material, by the rationale of the system of gathering and processing and by the training of the service personnel to carry out the suggested form of calculation.

The completeness of data is understood as the presence of all information required to carry out the calculation and analysis of maintainability of both the aircraft as a whole and of its individual apparatus. /137

The uniformity of data is assumed to be division of it into groups for analysis, which have the same properties in part of the conditions of operation and maintenance, nomenclature of the tools and devices used in repair, the qualifications of service personnel etc.

The timeliness of data is necessary primarily to take emergency steps to correct structural flaws which are revealed on the model and prototypes of an experimental consignment, upon transition to mass production of machines.

The continuity of reliable information is one of the main requirements on the system of organizing the calculation and gathering of data of maintainability. Continuity is necessary primarily in order that the data obtained during different stages of development, testing and operation of aircraft may be compared and that they permit analysis of the efficiency of operations to increase the maintainability of designs.

Data for calculation of the indicators of aircraft maintainability may be obtained by generalizing materials on maintenance and repair or by setting up and conducting special experiments. The observed time of operation of aircraft in cases of extensive investigation and conducting of special experiments is determined by the required accuracy of obtaining statistical data.

Materials on maintenance and repair are gathered according to the totality of aircraft in operation and according to a selective combination. In this case available accounts are used for the totality of aircraft, and special data are gathered for selective combination. The developed card file system is used in all cases to gather special data. The form of the card files and their content may vary as a function of the proposed purpose of conducting the investigation.

The card files should include questions, answers to which would ensure receipt of the required information for complete analysis of maintainability of the considered aircraft or of its individual apparatus. Simultaneously with development of the form of the card file, procedural instructions are compiled for the personnel performing the work on calculation of the data. As indicated by practice, this contributes to a reduction of the periods and an increase of the quality of filling the card files.

The most effective is a centralized system of data gathering and processing, in which the filled card files are sent to a specific organization for processing. In a number of cases digital keypunch machines are used for this.

Thus, the data required for civil aviation aircraft for successful use of mechanical processing is first subjected to encoding, i.e., the names of the systems, apparatus, components, formulations of the causes of malfunctions and other information are replaced by ciphers (digital notations). This work is performed according to code manuals of fixed and variable symbols. /138

A single 80-column punchcard in punched from each encoded card file at the keypunch station. After checking, the punchcards are sorted by group symbols as a function of the posed problem. The group symbols are arranged in specific columns of the punchcards according to the model of perforation used. The sorted data is transmitted to tabulation for processing by special programs.

The data obtained in this manner are still inadequate or incomplete in a number of cases. Special experiments are conducted in order to fill in the existing gaps. The main purpose of conducting such experiments to determine the level of indicators of maintainability is to obtain the omitted data, to reduce the time of receiving the data, and if possible to reduce expenditures of resources.

The main types of experimental checks are: under-control maintenance of a group of aircraft under near-real conditions; accelerated operation of a group of aircraft; simulation of the aircraft operation and repair process on electronic digital computers.

The main purpose of under-control maintenance of a group of aircraft is to analyze their efficiency, as well as to obtain materials for calculation of operative and economic indicators of maintenance.

The advantage of this method of obtaining statistical data includes a considerable reduction of the time required to obtain the data, as well as the possibility of obtaining all the required data for analysis of maintainability. The disadvantage of the method is the comparatively high cost of obtaining the data.

The method of accelerated operation of a group of aircraft reduces the time of obtaining the data with respect to individual indicators or properties of interest, which is usually achieved by forced loading or forced effects of external factors. The disadvantage of the given method is the considerable difference of the experimental conditions from those of real operation, which leads in a number of cases to distortion of the values of indicators of maintainability.

Simulation of the process of aircraft operation in order to determine the values of indicators and for analysis of the maintainability of their designs may be accomplished by methods of statistical and physical modeling. /1

As is well known, the essence of the method of statistical modeling consists in construction of an algorithm of the process of operation and restoration of the efficiency of an aircraft, which simulates the behavior of its individual components and the interaction between them under the effects of random perturbing factors. The essence of the method of physical modeling is in construction of an electrical analog of the investigated aircraft system and testing of it in order to investigate the processes which occur as a function of the initial given conditions.

We considered some questions of simulation in problems of maintainability in Chapter 3. A number of methods are suggested in [14] for solving problems of reliability and operation on standard electronic digital computers which may essentially be used to investigate the problems of maintainability of aircraft designs.

CHAPTER 5
PROVIDING FOR THE MAINTAINABILITY OF AIRCRAFT DURING THEIR DEVELOPMENT

1. Consideration of Requirements of Maintainability During Aircraft Development

In recent years there has been successful transition in the aviation industry to production of new and more improved types of transport aircraft. Their designs and technical flight data are being improved continuously.

There are good examples in the operational practice of design organizations where assemblies of systems are carried out in compartments and on removable panels. Hydraulic and gas lines and radio wiring through the fuselage and wings are laid in special conduits, which protects the wiring from damage, eliminates the possibility of short circuiting and makes them convenient for maintenance and routine repair. A great deal of attention in development of new types of aircraft is being devoted to problems of unitization and standardization of apparatus, assemblies and finished components. However, the designs of some types of air- /140 craft are still insufficiently complete from the point of view of their maintainability.

There are rare cases when wiring of systems is carried out by different methods even on aircraft of the same design organization, which is often unjustifiably complicated by introduction of additional apparatus, an increase in the length of wires, complexity and different types of connectors used etc. [28].

The requirements of technological effectiveness and specifications of the customer in provision of maintainability must be taken into account during the design of an aircraft.

The requirements placed on the design from the point of view of production may coincide in a number of cases, but may also contradict the requirements which follow from the operational conditions of the aircraft. For example, the common (coincidental) requirements are those such as division of apparatus into compartments and panels; assembly of equipment in special compartments and on removable panels; provision of communications connectors at the junctions of apparatus, compartments and panels; a reduction of the number of connections and simplification of them; and an increase of the interchangeability of components, assemblies and apparatus.

However, an increase of maintainability is achieved in some cases due to complication of the design and the techniques of producing it (replacement of non-detachable with detachable connections, division of one component into two to separate a part subject to severe wear into a separate easily removable component, execution of a large number of operational hatches for access to the assemblies and apparatus etc.). The optimum solution in each specific case should be found with consideration of the total expenditures for design, production, and also maintenance and repair during operation.

Unfortunately, some designers and technologists are usually very unwilling to satisfy the requirements of maintainability, if this restricts to some degree the production requirements, and deteriorates the technical and economic indicators of production processes. The following factors, in particular, contribute to this to a considerable degree: improper interpretation by the manufacturers of the concept of the technological effectiveness of the design as a combination of only those properties which make it possible to use the most improved technological processes for manufacture of it; and inadequate study of the problems of maintainability and incomplete consideration of requirements for providing maintainability.

According to existing practice, analysis of the technological effectiveness of an aircraft design is provided on the basis of analysis of the materials of the preliminary design, and then of the contract and detail designs. However, this is done only from positions of simplicity and convenience of manufacturing the aircraft.

The maintainability of a newly developed aircraft, insofar /141
as is possible, is first evaluated during discussion of the materials presented by the model committee. After consideration of the model, the representatives of the customer usually present numerous requirements on changing the design of the article to improve its maintainability, but they are too late. The design offices take into account only a small portion of the requirements presented, which reduces only to introduction of minor improvements. Problems related to reconfiguration of assemblies and apparatus and fundamental changes of the design of individual components, connectors, and assembly diagrams are usually not considered. And this is quite understandable, because such problems should be solved during the development stage of the design, when the airframe is being broken down into units, the units into panels and assemblies, clarification of the main connectors, etc.

Therefore, even in the 1960's the State Scientific Research Institute of Civil Aviation was faced with the problem of development and justification of the overall specifications to provide maintainability of the designs of newly developed types of aircraft. The specifications were worked out on the basis of data from analysis of the designs of existing types of Soviet and foreign aircraft from the point of view of their adaptability to maintenance and repair. Moreover, the reasons restricting a further increase of the repair cycle operating life of aircraft and successful introduction of progressive methods of maintenance and repair were also analyzed; the actual labor expenditures, idle times of the aircraft and expenditures for materials and spare parts during maintenance and repair were calculated.

The specifications on provision of maintainability include the following aspects:

- general aspects;
- requirements on the design for adaptability to progressive methods of maintenance and repair;
- requirements on the design in performing lubrication, control and checking, control and adjusting, recharging and other types of operations;
- requirements on the constructive execution and disposition of individual systems and assemblies on the aircraft, including requirements of their unitization and standardization;
- indicators of maintainability and their level.

The requirements with respect to the adaptability of the aircraft to progressive methods of performing maintenance and repair follow from analysis of the methods used in practice and the trends of their development with consideration of the best worldwide advances, possibilities and prospects for development of the Soviet aviation industry.

The designs of new aircraft should provide the possibility of extensive operational use of the apparatus-assembly method of / repair, the method of replacement and repair of apparatus according to the actual technical condition, the method of routine checking of the parameters of apparatus and units without removal from the aircraft and other progressive methods.

This is achieved first by use of the "fail-safe" principle during design due to redundancy, when a random failure in the operation of an individual component, apparatus and even a system does not lead to failure of the aircraft; secondly, due to the fact that the apparatus, assemblies and systems of the aircraft can be checked, i.e., they have built-in sensors and connecting points for periodic checking of their technical condition with the aid of monitoring devices; and third, requirements are carried out during design and manufacture of the aircraft with respect to interchangeability, accessibility and ease of disassembly of all removable apparatus and assemblies.

The main content of the section of requirements in the part performance of lubrication, control fastening, and control regulating operations leads to:

- minimization of the number and standardization of the types of lubricants, oils and devices used for lubrication of sliding surfaces;
- provision of easy access to threaded connections, which require checking of the tightening of bolts, reduction of the number of sizes of mounting components, and standardization of wrench size of bolt heads and nuts;
- provision of built-in sensors and output devices in apparatus, components and units for measurement of the determining parameters during maintenance without removing them from the aircraft, and standardization of the connecting points (connections, plugs etc.) to connect the aircraft to the control and measuring apparatus.

The section of requirements with respect to constructive execution and disposition of individual systems, apparatus and assemblies on the aircraft usually contains materials on:

- provision of accessibility, ease of disassembly and interchangeability of apparatus, assemblies and units during maintenance and repair;
- grouping of replaceable apparatus and units into large assembly packs (panels) and disposition of them in specialized compartments which provide normal working conditions for the service personnel in these compartments.

The investigations and many years of practice of maintenance and repair of aircraft in civil aviation enterprises permit us to state that work on providing the required level of maintainability is successful only in those cases when it is carried out with complete consideration of the specifications of the customer at all stages of development of the aircraft, beginning with the preliminary design.

This aspect has also been confirmed in foreign practice of aircraft construction. Thus, when developing the multiplace passenger aircraft Boeing-747, the company took a number of /1
steps to provide maintainability of its design.

First, the company instilled all designers and technologists, including the assemblers, with a feeling of responsibility for introduction of the principles of maintainability. For this purpose the designers and technologists continuously received data on the practice of operating the aircraft in the airline companies, and they also studied the practice of providing maintainability of aircraft structures during their design and manufacture.

The company devoted special attention to providing the maintainability of components, apparatus and assemblies which have a high initial cost and large expenditures for repair and maintenance, and also cause delays in the departures of aircraft and postponement of flights.

More than 250 nomenclatures of such assemblies and apparatus were selected and the necessary changes were introduced after detailed development in the aircraft design.

Engineers of the company, involved in providing maintainability, were combined into nine groups, organized according to functional feature: the aircraft design, hydraulic systems, landing gear, aircraft control, power plants, air-conditioning system, electrical equipment, radio electronic equipment, and the internal equipment of the cabins. The specialists of these groups observe that the proposals of the customers are reflected in the preliminary designs and detailed drawings in the section of increasing the maintainability, and also participate in checking the maintainability of the design during presentation of the aircraft mockup and during testing of the experimental prototypes. Moreover, they perform detailed analysis of the maintainability of the design on the basis of materials gathered on maintenance and repair.

According to available data, similar groups of specialists are also working in other American, English and French companies.

Considering the problems of taking into account the requirements of maintainability during development of an aircraft, it is appropriate to note that in a number of cases the customer's specifications in this area are stipulated in the contracts and become compulsory for the companies to execute. Thus, representatives of the United States Navy, in concluding a contract with the LTV Company for production and delivery of the A-7A aircraft, wrote that the labor expenditures for its maintenance and repair should not exceed 11.5 man-hours per hour of accrued flight time. If the company did not fulfill this requirement, a complex system of fines for each extra man-hour, expended on maintenance and repair above the 11.5 figure, was provided. The maximum value of labor expenditures was established at 17 man-hours per hour of accrued flight time.

If it were established during analysis that the labor expenditures for maintenance and repair of the A-7A aircraft were 17 man-hours per hour of accrued flight time, the company was obligated /144 to pay a fine of $875,000. If the labor expenditure was more than 17 man-hours per hour of accrued flight time, the company had to correct at its own expense all deficiencies which affect labor expenditures during maintenance and repair, in order to reduce labor expenditures to the established maximum level.

The actual labor expenditures for maintenance and repair of the A-7A aircraft were 9.59 man-hours per hour of accrued flight time. The LTV Company explains this success by the special attention which was devoted by the designers and technologists to problems of providing maintainability of the design during the early stages of development of the aircraft [43].

Thus, the primary and main condition of success in solving problems of providing the maintainability of designs is complete consideration of the customer's specifications in the given area during design, production and testing of the aircraft.

Using the results of the investigations on analysis of aircraft designs, and generalization of the experience of their maintenance and repair, let us consider some of the possible ways of providing maintainability of transport aircraft.

2. Provision of Accessibility to Objects of Maintenance and Repair

Basic Requirements

1. The equipment of the systems must be grouped in several large assembly units and be arranged in panels in specialized

technical compartments. The assemblies, apparatus and units of a single and a maximum of two aircraft systems should be located in each compartment.

The equipment in the compartments should be disposed in order to reduce to a minimum or complete cases when inspection or replacement of one of the apparatus is impossible without preliminary disassembly of other apparatus located alongside.

The apparatus, releasable connection, removable assemblies and components should be located at a distance of not less than 50 mm from the cover and walls for convenience of disassembly and assembly.

2. The hatches in the skin of the airframe should be located strictly opposite the points of installation of the corresponding assemblies, apparatus and components and their connections, requiring inspection during operaiton. The minimum dimensions of the hatches, depending on the nature of the operations performed, should be no less than 200 mm when performing an operation with one hand, and no less than 250 mm when performing an operation with two hands.

3. Access to the nuts of connecting bolts of fuselage parts should be accomplished by opening easily removed tapes without disruption of the entirety of the internal configuration of the /145 aircraft cabins and without removal of panels on large sections. The nuts of connecting bolts for attaching the hermetically sealed bottom of the fuselage should be installed on the side of the non-hermetic part of the fuselage.

4. Inspection hatches with easily removable covers or removable panels, which permit periodic close inspection of the condition of the internal primary structure of the center section and the skin during repair and maintenance of the aircraft, should be provided in the design of the center section.

5. The engine cowlings should be easy to open and in the open position should provide free access to all apparatus, assemblies and pipelines. Special attention should be devoted to providing accessbility to pipeline connections at points where the corresponding assemblies (according to the design execution) remain on the aircraft after removal of the engine, and also to assemblies for attaching the engine to the aircraft.

6. Access to the control system elements such as rods, transmission components, brackets, universal joints, reduction gears, rockers, rollers, and cables for their inspection, lubrication, regulation and replacement during maintenance should be provided by opening of easily removable panels (hatch covers).

Control wires for the engines, trim tabs, landing gear locks and others along their entire length, as well as the points of their connection and guides should be thoroughly scanned after completion of simple additional operations such as opening of the hatch, disassembly of the panel or elements of the internal equipment.

7. Inspection and lubrication of the bearings of the rudder suspension assemblies, flaps, ailerons, trim tabs, and servocompensators should be accomplished during maintenance without removal of the assemblies (rudders, flaps etc.).

The design of attaching the flap rails should provide convenience of removal and installation (replacement) of them during repair and maintenance. Lubrication of propeller machanisms, flap pins and carriages should be provided without removal of them from the aircraft.

8. Pressure leads of control rods and wires should be located primarily outside the hermetic part of the fuselage. Replacement of packing elements and pressure leads should be accomplished without performance of additional labor expenditure operations.

9. The landing gear design should make it possible to carry out lubrication of all articulated joints without raising the landing gear struts while providing convenient access to all lubrication fittings of articulated joints, mechanisms and elements of the landing gear structure, locks and doors.

10. Fill pumps should be located in places which have free access for maintenance and replacement through hatches that can be opened rapidly, in particular on the walls of the front and rear wing spars.

If the fuel pumps are located behind the supporting panels above or below the wing, these panels should be attached with reliable quick-response locks. /146

11. The central switchboards (CS) of the electrical equipment should be located in boxes, made of an insulated material or having an internal insulated cover, with provision of free access to the CS for maintenance.

12. The location and assembly of end switches, not contained in the structure of electrical mechanisms, should be performed with consideration of providing access for inspection and adjustment, as well as for cutting out of the network during replacement.

13. The radio equipment circuits should be installed on micromodule stacks. Replacement of one circuit should not require disassembly of the others, not subject to removal of the circuits.

Disposition of switches on the switchboards and control consoles should provide free access to each of them for inspection and maintenance operation.

14. Instrument panels and switchboards with devices for providing easy access during inspection and replacement of instruments should be collapsible or easy to remove.

Some Examples

The problem of providing accessbility in development of new types of aircraft is solved in practice mainly along the line of panelling of assemblies, optimum location of equipment on the aircraft, and the use of rapidly removable panels, hatch covers and cowlings.

The basics of paneling are in designing. Paneling of /14
assemblies includes rational disposition of apparatus and pipelines, related to one or several systems, on common zonal panels.

Paneling, in which, for example, hundreds of distribution line elements of electrical systems can be assembled in several communications units, makes it possible to considerably improve the approaches to the apparatus, to reduce the number of communications connections, to regulate the wiring, and to reduce the length of communications.

Development of zonal wiring panels makes it possible to completely reorganize the technological process of production, and also maintenance and repair. In this case conditions are created for mechanization of assembly operations, which up until now have been less mechanized than any other operations.

The problems of paneling and location of the hydraulic system apparatus on the IL-62 aircraft have been very successfully resolved. The panel for the hydraulic apparatus of the spoiler control is shown in Figure 54. Convenient access for maintenance and replacement if necessary is provided to all apparatus.

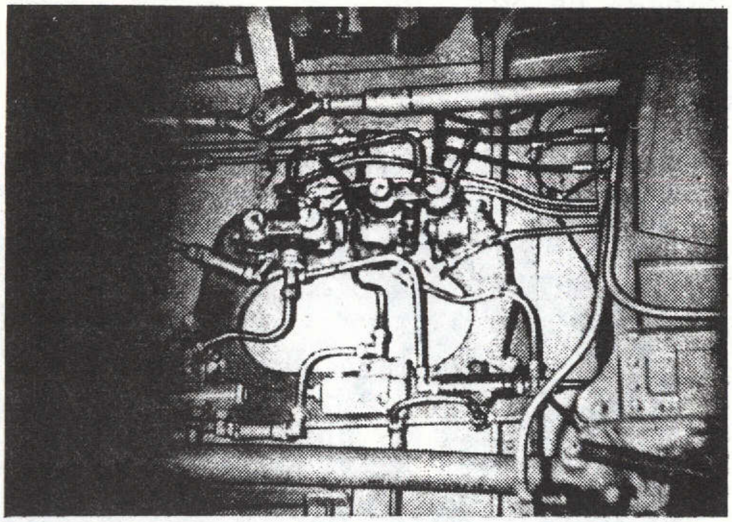

Figure 54. Panel of hydraulic apparatus of the spoiler control of the IL-62 aircraft.

A good example may also be the location of the hydraulic apparatus of this aircraft in the recesses of the front and main landing gear struts (Figure 55 and 56). Excellent access to the apparatus is provided with this solution and, moreover, the control apparatus are located in direct proximity to the members which they control. This contributed to reduction of the length of distribution lines of the hydraulic systems and to a decrease of weight.

Disposition of the apparatus on panels in the technical compartments is also practiced on many foreign aircraft. Thus, for convenience of maintenance and repair of the BAC-111 aircraft, all its main equipment is grouped in several specialized compartments:

- the electrical equipment — in the forward part of the fuselage;

- the hydraulic system — in the middle part of the fuselage, below;

- the air-conditioning equipment — in the middle part of the fuselage, below;

- the auxiliary generator plant — in the tail section of the fuselage (Figure 57).

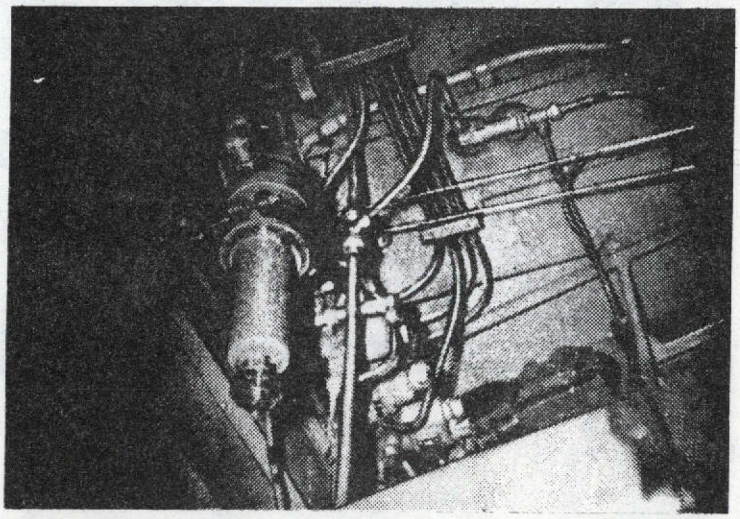

Figure 55. Disposition of hydraulic apparatus in the recess of the front landing gear leg of the IL-62 aircraft.

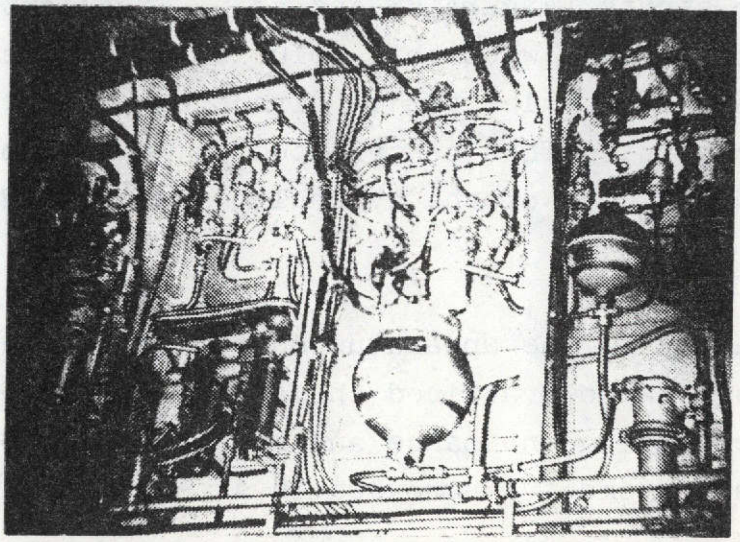

Figure 56. Disposition of hydraulic apparatus in the recess of the main landing gear leg of the IL-62 aircraft.

All panels which provide access to maintenance objects have larger dimensions; they are secured with the aid of rapid locks.

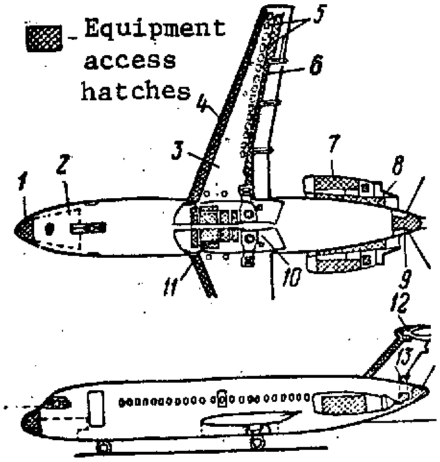

Figure 57. Diagram of the disposition of equipment for the main systems of the BAC-111 aircraft:

1- radar; 2- electric power plant; 3- fuel tanks; 4- removable leading edge of wing; 5- operational hatches; 6- control system apparatus; 7- engine; 8- cabin blower system; 9- auxiliary power plant; 10- hydraulic system apparatus; 11- air-conditioning system; 12- elevator control device; 13- rudder servomotor.

In order to work with the electronic equipment, for example, the panels on the lower part of the fuselage in front of the doors of the forward landing gear compartment must be removed. Ladders are not needed in this case. There is a wide compartment below in which one person can easily work. There is a panel in front of the hatch for the automatic pilot apparatus with standard plug-and-socket connections, which makes it easy to replace the necessary apparatus. /148

Serious attention is being devoted in development of aircraft to problems of providing accessibility to individual important apparatus and assemblies. There are a number of successful solutions.

Thus, the example of successful disposition of the fuel pumps may be cited for the A-10 aircraft. Here the pumps are located on the wall of the rear spar of the middle portions of the wing rather than behind the wing support panels as is usually done. There are openings, framed with duralumin coverplates, for the /149
fuel pumps, the recharging flanges of the fuel tanks, the

fuel tanks, and the fuel supply lines for the engines. Access to the pumps, control apparatus and electrical equipment, located on the rear wing spar, is accomplished by opening five swiveling panels. The panels are connected to each other with the aid of the connections, secured with locks along the trailing-edge ribs. Moreover, each panel is secured to the angular stringer of the trailing-edge of the wing and to the trailing-edge ribs with the aid of pins and spring locks.

Different types of equipment, control rods, wires and pipelines, required in routine maintenance, are usually installed on the front wing spar of a passenger aircraft of any type. Therefore, under operational conditions, easy access to the forward wing spar is required. However, this access has not yet been provided on all types of aircraft.

The given problem has been successfully solved, for example, on the I-18 aircraft. Hatches for access to the forward spar have been made along the entire length of the lower surface of the wing leading edge of this aircraft. The hatch covers are attached on hinges to the lower spar boom and on easily opened screw locks to the leading edges of the ribs and to the section on the boundary of the de-icing panels. This makes it possible to rapidly and reliably inspect the forward spar of the center section under operational conditions, and also to service the apparatus and pipelines, for example, the pipelines for the hydraulic, fuel and nitrogen systems, the engine control wires, the pipelines for taking air from the engines, and the electric wire bundles, located in the wing leading edges.

The successful solution of the problem of servicing the wing and aileron controls on the A-10 aircraft, from the point of view of maintainability, may also be cited as an example. Access to the control apparatus, located on the rear wing spar, is accomplished by opening five collapsible panels of comparatively large dimensions. The panels are attached by locks along the trailing-edge ribs and, moreover, to the angular stringer of the wing trailing-edge and the ribs by pins and spring locks. The panels open very rapidly, after which good access is provided for inspection of the rods, transmission shafts, suspensions and wall of the rear wing spar, and also for performance of lubrication and checking-regulating operations.

Routine maintenance and replacement of elevator apparatus are carried out on aircraft with pressurized cabins along with other procedures during operation. Replacement of apparatus is carried out both due to completion of the operating lifetime and in the case of malfunction.

Servicing of the elevator equipment is simple on the I-18 aircraft, since free access to all apparatus is provided to perform maintenance. Thus, one block of the blower system apparatus is located in the large hydraulic compartment in the region of frame No. 8 near the right side of the fuselage. Access to the compartment is accomplished through a side door as high as a man. The apparatus are closed by an easily removable housing. The second block of apparatus is located in the rear toilet, where easy access to the apparatus is also provided.

Through joint efforts during designing, the designers of the I-62 aircraft and its engines provided free access to all engine apparatus and pipelines by opening of the two cowling doors. In particular, servicing, disassembly and assembly are possible with such apparatus as the generator, the constant-speed drive, the fuel filter block, the automatic fuel flow meter, the force fuel pump etc.

Easy access to many apparatus of the elevator and de-icing systems is also provided on this aircraft.

Thus, excellent accessibility is provided to any of the dampers of the de-icing system of the wing (Figure 58) to perform operations of maintenance and replacement if necessary.

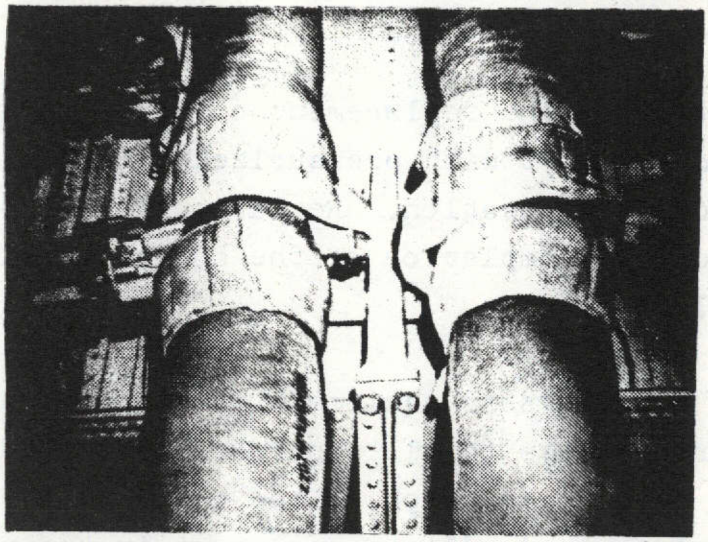

Figure 58. Provision of accessibility to the dampers of the wing de-icing system.

However, the factor of accessibility was not taken into account completely when locating the circular dampers of the de-icing system of the stabilizer (Figure 59).

As can be seen, the lower damper must first be removed in order to replace the upper damper with this design solution. In the given case the hatch of the upper surface of the tailplane front must be provided to improve access to the upper cyclic damper. /150

There are numerous examples of successful design and productive solutions on provision of maintainability on other aircraft, in particular, on the YaK-40, Tu-134 and Tu-154 aircraft.

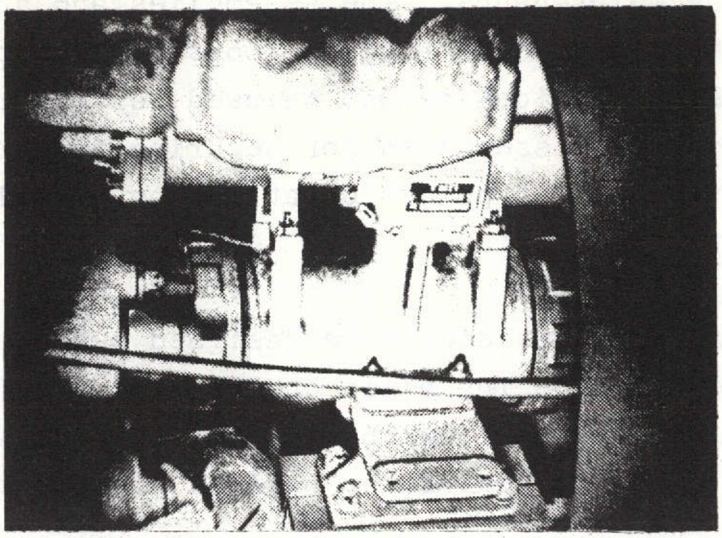

Figure 59. Installation of cyclic dampers of the de-icing system of the tailplane (view from below, lower damper removed).

3. Provision of Easy Removal of Objects for Maintenance and Repair

Basic Requirements

1. When designing complex aircraft and apparatus, the possibility of removal under operating conditions of individual components which have a shorter operating life must be provided in order to perform intermediate inspection and repair of them without removal from the aircraft and subsequent disassembly of the entire assembly (apparatus).

The connections subject to disassembly and assembly during operation and repair should be built in such a way that any possibility of their improper assembly is excluded.

2. The possibility of performing operations by the efforts of two men should be provided for apparatus and assemblies weighing from 20 to 50 kg, which are subject to routine removal from the

aircraft during maintenance. The assemblies and apparatus weighing more than 50 kg should have rigging loops for hoisting devices. If ground hoisting devices cannot be used, easily removable hoisting devices and assemblies for securing them to the aircraft should be provided. The points of attachment should be noted by the appropriate inscriptions.

3. The power plant should be designed such that the engines may be removed from and installed on the aircraft fully assembled together with the braces, cowlings, lubrication system (with the oil tank) and other apparatus, as well as without the cowling.

Preliminary and finishing operations, performed on the power plant immediately prior to removal of the engine from the aircraft and after installation of it on the aircraft, and also adjusting operations of a newly installed engine should be reduced to a minimum.

Connections of the engine pipelines (hoses, conduits, electric wires etc.), of the ignition system and assemblies for attaching the engine to the aircraft should be easy to disconnect.

The fuel and oil filters of the power plant should be located in accessible places, which make it possible for the service personnel to work with two hands. Rapid and easy removal of the fuel and oil filter caps should be provided.

4. Replacement of the fuel pumps should be performed without preliminary drainage of fuel from the tanks, suspending the wing on hoists and without the necessity of access to the inside of the tanks. The pumps are located in positions which make it possible for the service personnel to replace them easily.

The fuel lines at the points of connection to the pumps should be executed in the form of flexible hoses of kerosene-resistant rubber to facilitate disassembly and assembly of the pumps.

5. The fillets of the butt connections of the wing, vertical /152 stabilizer and tailplane to the fuselage, as well as the coverings of their tail section should be secured by means of locks (screws), designed for repeated use. Hatches should be provided for convenience of inspecting the technical condition of the butt connections of the wing, tailplane and vertical stabilizer to the fuselage, and also the brackets for suspending the rudders and ailerons in the fillets and coverings, respectively.

All hatch covers are attached by means of quick-response locks of the same type, which are more convenient and which have recommended themselves well in operation. The locks for attaching the hatch covers should be standardized and interchangeable.

Replacement of the locks during maintenance and repair of the aircraft should be performed without the necessity of removing the rivets from the skin.

6. The heads of the locking bolts for attaching the fuselage to the center section, the center section to the removable part of the wing, the fuselage to the vertical stabilizer and tailplane, and also the bolts for attaching the assemblies, brackets, apparatus and other components of the aircraft, located in positions of the fuselage, wing and tail assembly which are difficult to reach and which pass through blind walls, should be secured against turning and falling out.

The heads of bolts for attaching pressure leads should be located on the side of the pressurized part of the fuselage and secured against turning and falling out during disassembly and assembly operations.

7. The design of the landing gear legs and the assemblies for attaching them to the aircraft should make it possible to replace completely assemblied forward and main landing gear legs if necessary. The number of components and articles, reinstalled from a removed landing gear leg to a newly installed one, should be reduced to a minimum.

Easy removal of the cylinders for retracting and extending the landing gear, the cylinders for the carriage shock absorbers (stabilizing absorbers), the wheels, brakes, wheel bearings and bushings should be provided. The wheel axles should be protected against corrosion and "seizure" against the inner races of the bearings.

8. The apparatus of the elevator equipment should be attached primarily by rapid locks (coupling collars and special detachable locking devices), which make it possible to perform rapid replacement of them during maintenance.

When replacing the apparatus of the elevator system, subsequent checking of the seal of the entire line is not usually required.

9. The removable floor panel in the crew cabins and passenger lounges should be of small size and attached by quick-response locks (screws) of the same type, secured to prevent falling into the subfloor space. The number of locks (screws) for attaching the panels should be minimum.

The design of attaching the floor panels should permit rapid /153
replacement (repair) during maintenance of any malfunctioning panel without preliminary disassembly of the panels located alongside.

The ceiling panels, which provide access to the electrical wiring, apparatus of the electrical and radio equipment, and the control rods and wires, should have an articulated suspension and be attached in the closed position by rapid locks.

10. The chemical fluid tanks, filters, pumps, drain pipes, and also the other equipment of the sanitary apparatus, located in the subfloor section of the fuselage, should be located in the pressurized cabin, preferably in easily removable containers.

11. The configuration of the electrical packing material, stuffing boxes and the structure for attachment of them should provide the possibility of repair of the network, usually by replacement of all the packing, sections of the network and individual wires under operational conditions without the necessity of disconnecting parts of the aircraft and dismantling its apparatus.

12. Installation and attachment of electrical mechanisms should provide the possibility of free disconnection of them from the drive member in all its positions.

Replacement of brushes on the generators (starter generators) should be performed without the need for removing the generators from the aircraft engines.

13. The connections of the radio equipment blocks, switchboards and control consoles to the aircraft wiring should be accomplished primarily with the aid of self-centering grooved connections.

Constructive execution of the aircraft radio equipment connections should completely exclude the possibility of incorrect connections.

The automatic control systems (ACS) on the I-62 aircraft are located on the micromodule stack of the navigation equipment in the zone of rib No. 11 (Figure 60). Besides providing free access, the units are easy to remove during maintenance.

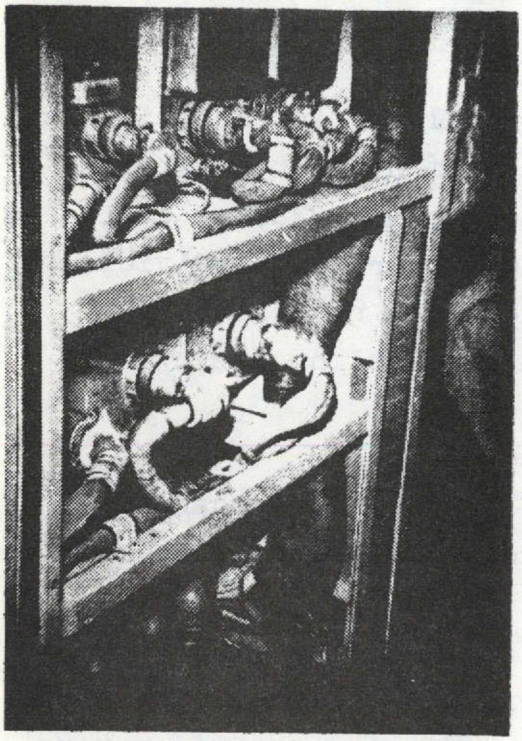

Figure 60. Location of ACS units on the I-62 aircraft.

Easy removal of the pressure leads of the elevator and rudder control rods is provided on the I-18 aircraft by their location. The pressure lead is located in the upper section of the spherical bottom on the side of the unpressurized part of the fuselage (Figure 61). It is a cast bracket 6, through the walls of which pass the elevator and rudder control shafts. The bracket is enclosed by walls on all sides except one. The open side is turned toward the bottom of the cabin, and, together with the bottom, the bracket forms a closed and sealed cavity. The shafts passing through the walls of the bracket are sealed by round rubber gaskets. Each shaft operates independently of the other, because they are not connected to each other. There is free access to the pressure lead on the side of the rear baggage compartment; servicing and replacement of the pressure lead are easy and rapid.

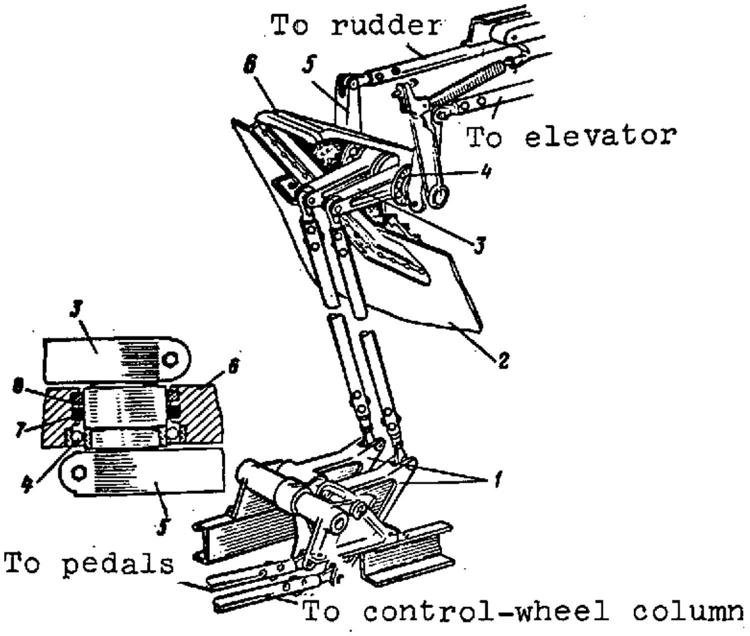

Figure 61. Pressure lead of the elevator and rudder control rods of the IL-18 aircraft:

1- rocker; 2- bottom of pressurized cabin; 3- rockers in the pressurized cabin; 4- bearing; 5- rockers outside the pressurized cabin; 6- bracket; 7- rubber packing ring; 8- felt ring.

A number of examples of providing easy removal may be cited for foreign aircraft. Thus, the basis of the design of the DC-9 aircraft contained the following principles:

- simplification of the systems by reducing the number of apparatus;
- use of apparatus whose reliability was checked in operation;
- provision of easy access to apparatus requiring frequent inspection and maintenance;
- extensive use of quickly detachable connections, cheese couplings and simple fastenings, providing easy removal;
- a minimum set of special hand tools.

When the design of the aircraft was completed and all important operations on maintenance were checked under real conditions, it /155 was established that in a number of cases considerable improvements from the viewpoint of maintenance could be achieved by simple modifications.

Data on the time required for replacement of individual apparatus of the DC-9 power plant are presented in Table 27.

TABLE 27.

Component	Time of replacement, minutes	
	Provided during design	actually obtained
Engine	60	38
Nose fairing	30	20
Auxiliary power plant	60	18
Oil cooler of constant-speed drive	30	21
Constant-speed drive	60	45
Generator	30	25
Hydraulic pump	30	20
Heat exchanger	60	60
Reverse thrust booster	48	15
Starter	30	12
Auxiliary hydraulic pump	18	11
Hydraulic system filter	12	4
Blower for ground cooling of passenger cabin	30	5

Let us consider by what methods the problems of providing ease of removal were solved. Thus, the engine nose fairing was initially secured by 23 screws. During preliminary design, it was decided to secure it with the aid of four self-tightening screws. Upon final modification, the number of screws was increased from 4 to 12 with introduction of two regulating pins. Because of these improvements, the nose fairing may be replaced within 20 minutes by two specialists. This is especially important, because replacement of the nose fairing is necessary in relocating the engine from the left to the right position.

Installation of the constant-speed drive oil cooler on the same aircraft was simplified considerably by improving the design of the cooler attachment. Elimination of the cooling air corrector pipes made it possible to reduce the time of maintenance of the cooler.

The covers of hatches opened often for maintenance of the engine lubrication system and constant speed drive were initially attached at 6-8 points each. After modifications on each of the covers, only two spring-loaded button locks were installed on each.

A great deal of attention was devoted to problems of facilitating transfer of the engine from the left to the right position by reducing the number of "asymmetrical" parts. The nose fairing, the pipes for supply of air to the starter and the three conical assembly bolts are "asymmetrical". Because of this, preparation of the power plant for suspension from the left or right side occupies a minimum of time.

It should be noted that power plants are delivered in assembled form to the operational enterprises. The mounting pipes of the systems are installed on both sides, and the electric wiring gaskets, unfolding in a spiral, are located above and below the engine. The starter air conduits (left and right) and the conical assembly bolts are part of the engine. After it has been determined from which side the engine should be installed, the necessary wiring is completed, the corresponding air conduits and conical bolts are installed and the engine is ready for installation on the aircraft. Replacement of the engine on the aircraft, including the engine equipment for installation on the corresponding side and replacement of the nose fairing, is performed within 40 minutes.

The engines on the F-28 Followship aircraft of the Fokker Company are installed in cowlings in the tail section of the fuselage. The design permits installation of a completely equipped cowling without the engine on the aircraft, and also rapid replacement of the engine without removing the cowling. Large collapsible panels provide access to the engine along the entire length within the limits of 190° circumference. Small hatches, which make it possible to check the engine oil system and the oil tank of the constant-speed drive system, are provided in these panels for rapid maintenance between flights. /156

When the hoisting device, installed in the upper section of the cowling and designed by the Fokker Company, is used, the engine may be replaced by five men within 48 minutes if there is a prepared rapid replaceable power plant. The power plant consists of the engine with all apparatus previously installed on it, the nose fairing, which connects it to the forward engine flange, and the exhaust pipe, attached on the rear flange. The only part of installation which is not identical for the left and right engines is the nose fairing. The exhaust pipes are identical, but during installation they are rotated in different directions with respect to the axis to provide proper removal of gases.

Problems of replacing the fuel pumps and a number of other fuel system parts have been solved successfully on the given aircraft.

Thus, each booster pump is mounted in a cannister facing the lower skin. The cannister may be disconnected and the fuel drained from it without draining the fuel from the tank, which facilitates replacement of the pump. Warning signals about failure of the pump are accomplished with aid of a pressure /157 relay, sensitive to pressure at the pump output, and a signal lamp on the fuel supply control console.

The isolation valves of the tanks and the ring valves, identical in design, are installed on the rear spar. These are spherical valves with an electric drive and graphite packing. The electric motor may be easily replaced without touching the valve.

Rigid fuel lines of light alloys having flexible connections are used everywhere, with the exception of the engine cowlings; steel pipes in combination with flexible hoses are installed in the cowlings.

All elements of the fuel system are designed for repair "if necessary" (depending on the condition of the components) and may be checked by simple means without disassembly. The service life (15,000 hours) is established only for two apparatus: the booster pump and the electric motor of the valve drive.

Most attention was devoted to problems of providing easy removal in development of the BAC-111 aircraft. As a result, the following values of the replacement time for individual important components of the aircraft were obtained (Table 28).

When developing the multiplace L-1011 aircraft, specialists of the Lockheed Company attempted to solve the problems of facilitating maintenance and repair of it, in particular, by providing easy removal of components. In connection with the fact that 20 instead of the existing 30 minutes are given for maintenance of the aircraft at intermediate airports, the time for replacement of many components requires no more than 20 minutes. Approximately 90% of all operations are planned to be completed within 1 hour. Replacement of the elevator requires 2 hours, that of the flap section 1 hour 15 minutes, the engine — 90 minutes, and the main landing gear wheel — 25 minutes.

TABLE 28.

Component	No. of men	Removal time	Installation time	Total replacement time
		Hrs.&min.	Hrs. & min.	Hrs. & min.
Wing fairing	1	0.20	0.20	0.40
Wing leading edge	4	0.30	0.30	1.00
Entrance door	2	0.15	0.25	0.40
Cargo door	2	0.10	0.10	0.20
Antenna fairing	3	0.10	0.15	0.25
Front windshield of pilot cockpit	2	1.00	1.00	2.00
Opening window of pilot cockpit	1	0.10	0.10	0.20
Passenger cabin window	1	0.10	0.20	0.30
Flap	2	0.25	0.50	1.15
Elevator hydraulic actuator	1	0.40	0.50	1.30
Forward landing gear leg (assembled)	2	1.45	2.15	4.00
Main landing gear leg (assembled)	3	2.30	3.00	5.30
Forward landing gear retraction and extension cylinder	1	0.20	0.25	0.45
Main landing gear retraction and extension cylinder	1	0.20	0.20	0.40
Temperature control valve	1	0.10	0.15	0.25
Heat exchanger	2	0.45	1.00	1.45
Exhaust valve	1	0.20	0.20	0.40
Hydraulic pump (on engine)	1	0.15	0.20	0.35
Aircraft hydraulic pump	2	0.30	1.00	1.30
Generator (on engine)	2	0.45	0.45	1.30
Engine with fairing, reverser and nozzle	4	1.00	1.20	2.20
Constant speed drive	1	0.30	0.30	1.00

The Douglas Company established the following norms for replacement of individual components of the DC-10 aircraft: engine — 60 minutes, auxiliary power plant — 45 minutes; generator — 30 minutes, main landing gear wheel cover — 12 minutes, cabin glazing — 60 minutes.

4. Provision of Interchangeability of Maintenance and Repair Objects

Basic Requirements

1. The apparatus, assemblies and components of an aircraft, removed and replaced during maintenance and repair, should have geometric and functional interchangeability. The requirement for high geometric interchangeability should be fulfilled primarily for the apparatus, assemblies and components of the airframe, which have a high frequency of replacement or long repair cycles. They include:

- the elevator and rudder;
- the ailerons, trailing-edge flaps, interceptors, leading-edge flaps and trim tabs;
- panels, hatch covers, fillets and fairings;
- engine cowlings, bracing struts, and frames for securing the engines;
- the entrance and cargo doors and locks;
- landing gear (assembled), locks and doors;
- pressure leads, control rods, rockers and mounting brackets;
- floor panels in the cabins and baggage compartments;
- wing leading edges and tail assemblies;
- window glass for passenger cabins and pilot cockpit.

2. The apparatus, components and units of aircraft systems and special equipment should have total geometric and functional interchangeability.

3. Design improvements in the aircraft (modifications) /158 should be carried out so that the altered (modified) parts and assemblies may replace parts (apparatus) of previous designs on all types of aircraft where they are installed.

4. Performance of adjusting operations if necessary, including joint reaming, drilling, cutting, riveting etc., should be accomplished with the aid of standardized tools, eliminating the use of special tools, equipment and materials.

5. To provide interchangeability of systems elements in the design, technological compensators must be provided which make it possible to install equipment, instruments, and mounting brackets, made with deviations within the tolerance limits. Compensation in the form of spacers, grooved washers, openings of increased diameters, elliptical openings, adjustable caps, and compensators for pipe displacements may be used.

6. Operational and repair accesses should be designed with consideration of preserving the necessary quality of the apparatus and assembly and the possibility of transferring it to another aircraft during maintenance and repair.

7. Replacement of pressurized components — entrance doors, hatch covers, cabin glass and others should be performed without additional pressurization of fuselage openings and of the pressure components themselves.

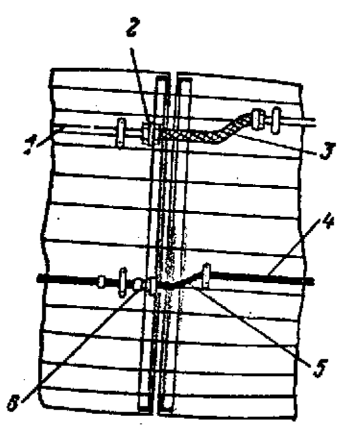

Figure 62. Compensators — flexible hoses and collars in pipeline links, located at the junctions of parts to the fuselage:

1- pipeline; 2- pipeline connection; 3- flexible compensator hose; 4- electric wire bundles; 5- free (not attached to frame) compensator electric wire bundle; 6- plug-and-socket connection.

8. Connections of the main electric and radio communication lines and pipelines of aircraft systems should be performed without the use of compensators during adjustment (Figure 62).

Methods of Providing Interchangeability

Dependent manufacture of components, assemblies and apparatus is usually employed in aircraft construction to provide interchangeability. Coordination of the shapes and sizes of components, assemblies and apparatus is accomplished with the aid of two- and three-dimensional templates of the shapes and sizes of the assemblies and their connections [9]. In this case fixed templates are mold lofts, master forms, surface standards, master plates and models of the connections. The dimensions are transferred from the rigid surfaces to the operating production line equipment.

Problems related to interchangeability are solved during /159 design and manufacture of the aircraft. The airframe is broken down into apparatus, compartments and assemblies in order to provide production and operational requirements; connections for articulation of systems and cutouts for access to the apparatus and assemblies in operation are provided.

As a result of dividing the structure into parts, a scheme is formulated for providing interchangeability, which reflects the relationship between the individual apparatus, compartments and systems of the aircraft. Mutual linking of the joints and connections of the engines, instruments and equipment to the joints and connections on the airframe is also accomplished according to the scheme of providing interchangeability.

All components and assemblies of the aircraft are divided into four groups as a function of the means of linking and providing interchangeability [22].

The first group of components and assemblies has comparatively simple geometric shapes, sufficient stiffness and may be manufactured and checked directly from the given drawing. In this case the connecting components are manufactured independently of each other and are checked by all-purpose devices according to the existing system of tolerances and checks.

The second group includes sheet and profile components, and also components and assemblies manufactured on metal-cutting equipment which have a three-dimensional shape with complex surfaces and which cannot be assigned in the drawings with the aid of simple numerical dimensions. The loft-template method of linking is used to provide the interchangeability of components of this group. In this method special surface master dies (of the apparatus or individual element of the apparatus) are manufactured, which indicate not only the dimensions, but the shapes of the surface as well. The direct copying method transfers the shape and dimensions of the surface master die to the profiling attachment, and then from the profiling attachment to the components.

The third group of components, assemblies and apparatus includes complex components, assembled and welded assemblies, related to shaping of the external surface, and also all pre-assembled panels, sections and apparatus.

Special equipment, manufactured with the aid of tool or assembly master dies, is used to provide a high degree of interchangeabiltty.

Accurate transfer of joint parameters from master dies to the article makes it possible to provide complete production and operation interchangeability.

The master die method is employed for almost all sections and main apparatus of the AN-25 airframe. This creates technological prerequisites of high interchangeability of assemblies. During manufacture of the access door of the Tu-134 aircraft, for example, a standard mockup is used, which provides /160 total interchangeability of the doors.

The interchangeability of apparatus according to these connections is provided to a considerable degree during final machining of the connections on special finishing benches.

Finally, the fourth group of components and assemblies includes assembly articles of equipment systems; unitized wiring panels, switchboard panels, boxes and blocks; and elements for attaching the enumerated components and assemblies to the chassis of the article.

In the given case interchangeability is achieved by installation of pipes which do not require bending and adjustment; installation of assembled electrical and radio wires in packing materials with terminals, connections and clamps on the article by elimination of processes related to broaching during installation. The interchangeability not only of the seats of the components and assemblies, but also of the configurations, as well as the mutual disposition of the components and assemblies on the article must be provided.

To solve this problem, a method is used of manufacturing full-scale models (sections), which completely simulate the chassis of the corresponding section of the article, but are made more rigid. Moreover, more convenient access is provided in them to control and inspect the wiring.

Operational experience shows that the greatest volume of adjusting operations is carried out during replacement of aircraft apparatus and assemblies, joined by structural operational connections. This group includes the main apparatus and assemblies of the airframe, the power plant, the landing gear and aircraft control. It is understandable that primary attention is devoted to problems of providing interchangeability of the enumerated apparatus.

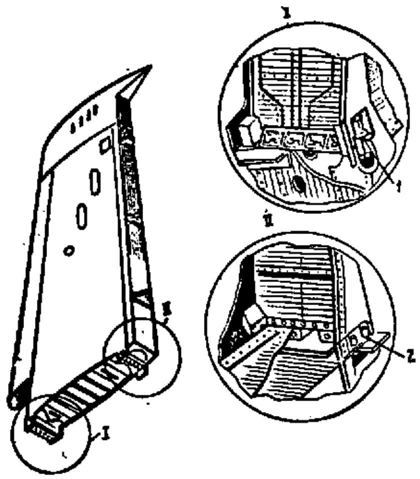

Figure 63. Flange connection of vertical stabilizer to the fuselage of the An-24 aircraft (bolts 1 and 2 are installed with a gap of 0.3 mm).

The use of flange connection of wing parts should be regarded as successful. Such connections are used on most types of civil aviation aircraft, designed under the supervision of A.N. Tupolev and O.K. Antonov. The use of structural compensation in the form of a difference in the diameters of the opening and bolt in the butt joint, equal to 0.1-0.3 mm, provides complete interchangeability of the removable parts of the wing at the flange connections during maintenance and repair.

Flange connections are also used for the vertical stabilizer and tailplane of An-24 aircraft (Figure 63), unlike tab connections, used on other types of aircraft (Figure 64). It should be noted that interchangeability of the tab connection is inferior to the interchangeability of the flange connection due to the absence of compensation in the former. /16

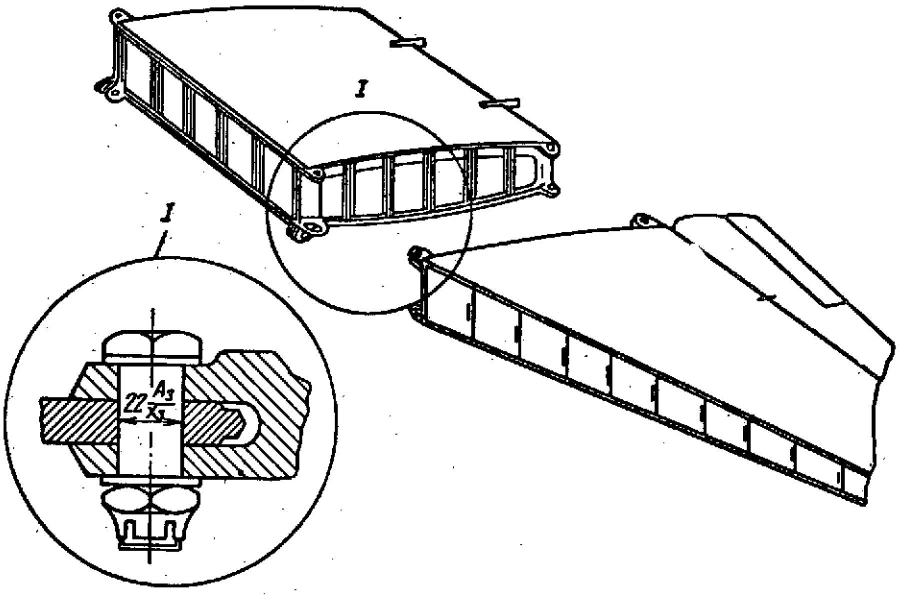

Figure 64. Tab connection of the removable part of the stabilizer to the center section of the Tu-124 aircraft.

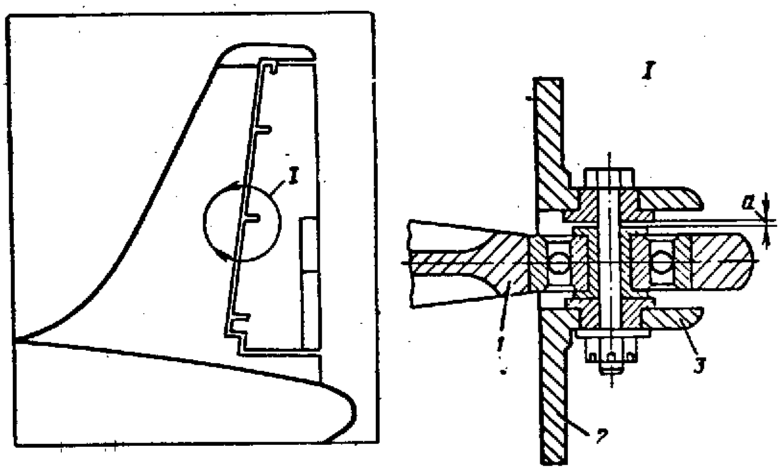

Figure 65. Rudder suspension assembly:

1- bracket support — vertical stabilizer tab; 2 and 3- bracket support — rudder yoke; a- gap in tab — yoke articulation, acting as a means of compensation.

The problem of providing interchangeability of rudders and ailerons is important for operation. Suspensions of rudders and ailerons of the tab — yoke type using structural compensation in the connection elements are more interchangeable. This method of suspension is used on most types of aircraft, in particular on the IL-18 aircraft (Figure 65).

The use of universal joints to suspend aileron assemblies is also a rational solution (Figure 66). The gap a and compensating washers 2 act as means of compensation in the given case.

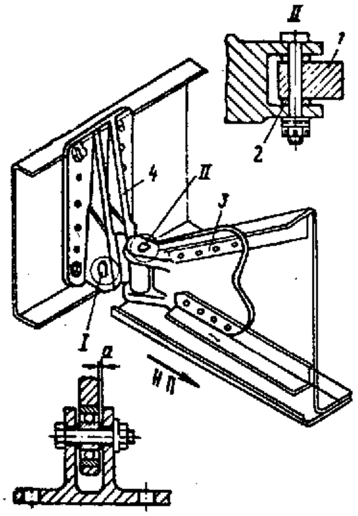

Figure 66. Aileron suspension assembly:

1- universal joint; 2- compensating washers; 3 and 4- bracket supports.

Considering the problem of providing the interchangeability of landing gear doors, which in a number of cases are replaced during maintenance and repair of aircraft, the following should be noted. The difficulty of providing complete interchangeability of doors is caused by their complex geometric shape and rigid tolerances according to the inscription in the outlines of the end gaps.

However, the interchangeability of doors in the suspension assemblies is provided on almost all types of aircraft. Of the two types of suspension assemblies (loop and joint) used in practice, a joint suspension with sliding bearings is preferable. Compensation of the radial and axial displacements of the suspension assemblies is used in the given design.

Fillets are geometrically complex structures which are curved in several planes. Adjustment of them on-site is a complicated and laborious process, which requires highly qualified specialists.

Examples of successful structural solutions of attaching fillets may be observed on the Tu-124, An-12 and other aircraft. For example, the wing-to-fuselage fillet on the Tu-124 aircraft is non-detachable. The joint of the mid-part of the wing to the fuselage is covered with a jointed band, adjustment of which is much simpler than that of fillets. The tailplane-to-fuselage fillet on the An-12 aircraft is non-detachable. The joint of the removable part of the tailplane to the center section is covered with a jointed band.

The access doors of most aircraft, assembled in building blocks, are installed on the fuselage with provision of compensation. The most convenient in production and operation is articulated connection of the doors, because it makes it possible to provide interchangeability by simple technological devices. Articulated connection of the doors is used on the Tu-104, Tu-134, An-12 and I-18 aircraft. The doors are sealed with rubber sections (Figure 67).

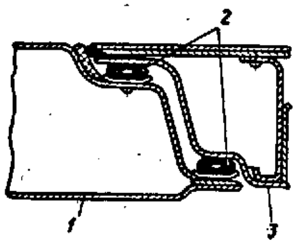

Figure 67. Sealing of the access doors of the I-18 aircraft with rubber sections without using a seal: 1- access door; 2- rubber sections; 3- fuselage.

High requirements of interchangeability are placed on the window glass of the passenger cabins and the pilot cockpit, because the glass requires frequent replacement. Glass is divided according to structure into glass with and without grooves, and according to the method of sealing — into that sealed with UZOMES-5 sealer and that sealed by rubber packing.

The use of glass without grooves sealed by rubber gaskets is /1
most successful on the I-18 and An-12 aircraft. Replacement of such glass does not require adjusting operations and such glass is completely interchangeable.

5. Providing the Adaptability of Designs for General Purpose Adjusting Operations

Lubrication Operations

Problems of the efficiency of the lubricated components of an aircraft, in particular, of articulated connections, may not be regarded separately from lubrication conditions, because the efficiency of components depends on the condition and behavior of the entire aggregate: metal — lubricating material — metal. Interruption of the normal lubricating conditions of the sliding surfaces of components and deterioration of the quality of the lubricant due to oxidation, dilution by fuel or contamination by mechanical impurities, accelerates the wear of components. Moreover, the amount of lubricant in the assemblies and apparatus gradually diminishes with time. Therefore, the condition and quantity of lubricant in the apparatus, assemblies and articulated connections must be checked periodically during operation of an aircraft.

The selection of lubricants and of the frequency of lubrication is a responsible stage of designing and should be carried out on the basis of calculation and thorough, extensive study of the operation of assemblies on aircraft of similar design under real operating conditions. Lubrication charts, in which the lubrication point, the lubrication cycle and the lubricant are indicated, are developed for each type of aircraft, as a supplement to the maintenance regulations (Figure 68). The content of the operations, the types of lubricants and the necessary devices for lubrication of the main landing gear leg of an aircraft are shown in Table 29.

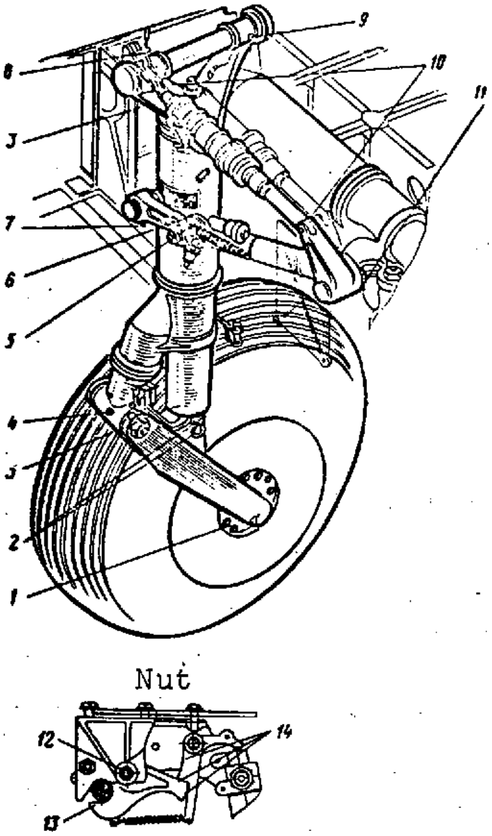

Figure 68. Lubrication chart of the main landing gear leg of an aircraft:

1- wheel bearing; 2- joining of connecting rod and crosspiece; 3- shock absorber rod and hydraulic lifter; 4- connection of crosspiece and two hooks; 5- articulated connections of strut lock; 6- middle joint of strut; 7- ball joint of lower strut link; 8- mechanical marker axle; 9- support pin of leg; 10- connections of hydraulic lifter to shock absorber and strut; 11- strut joint; 12- axle of locking hook of leg in retracted position; 13- mouth of locking hook; 14- sliding surfaces of hook and lock catch.

The lubricants used in Soviet machine assemblies may be considered as a type of structural material with properties which sometimes affect the efficiency of the friction surfaces no less

TABLE 29.

Content of operation	Form of routine maintenance and lubrication point				Device used for lubrication
	No. 2	No. 3	No. 4	No. 5	
Wipe clean with a cotton towel	4, 5, 6, 7, 8, 9, 10, 11, 13, 14	4, 5, 6, 7, 8, 9, 10, 11, 13, 14	4, 5, 6, 7, 8, 9, 10, 11, 13, 14	4, 5, 6, 7, 8, 9, 10, 11, 13, 14	—
Flush with kerosene	If necessary				—
Pour MK-8 inside the connections	5.8	5.8	5.8	5.8	Brush
Lubricate with TsIATIM-201	13.14	13.14	13.14	13.14	•
Squirt with TsIATIM-201 inside connections	2, 4, 6, 7, 9, 10, 11, 12	2, 4, 6, 7, 9, 10, 11, 12	2, 4, 6, 7, 9, 10, 11, 12	2, 4, 6, 7, 9, 10, 11, 12	Greese gun
Flush with clean gasoline	1	1	1	1	—
Recharge the recesses between the rollers and races with ST(NK-50) lubricant	1	1	1	1	Brush

than the properties of the material from which the lubricated components are manufactured. At the present time even more attention is devoted to selection of the lubricant for lubrication of the surfaces of components operating under strain and to constructive solution of delivering the lubricant to the surfaces of such components, than to selection of the material of the sliding surfaces. It is now well known that the use of lubricants with one or another special properties may sharply increase the wear-resistance and, consequently, the surface life of the friction surfaces.

When developing a new machine, the grade of lubricant must be carefully selected and conditions must be worked out for delivery to the lubricated surfaces both under conditions of manufacturing /164 the machine, and during oepration. However, these problems do not always find a satisfactory solution. There are frequent cases in aircraft maintenance when it is very difficult and sometimes even impossible to perform lubrication due to unsatisfactory access to the lubricating valves, their absence or poor location, and also for other reasons. A lubricant applied by hand without the use of a grease gun usually remains outside the sliding components and often does not reach the target. In many cases difficult access to the surface points is the cause of unsatisfactory lubrication.

To provide high quality of lubrication operations with the least expenditure of time and labor on the aircraft structure, the following main requirements may be set up.

1. Lubricants supplied by operational civil aviation enterprises should be used in assemblies and connections of the aircraft structure and its apparatus. In this case one should be limited if possible to a minimum number of types of lubricants.

2. The lubrication surfaces of the assemblies of articulation connections should hold the lubricant well and should be protected from dust, sand, and moisture in order that the lubricant replacement cycles will be longer.

The minimum period for lubrication (not less than every 300 hours of accrued flight time) for the modern transport aircraft /165 should be established only for individual assemblies and connections.. The main volume of lubrication operations should be performed during the more complicated forms of aircraft maintenance.

3. All the important parts of movable connections which require periodic renewal of the lubricant should have lubricating valves, which make it possible to perform high quality lubrication of sliding surfaces under pressure. The lubricating valves should be standardized according to design and wrench sizes and should be painted bright orange.

4. Access during maintenance with the necessary tools for lubrication should be provided for all lubricating valves and lubrication points of sliding surfaces.

Servicing Operations

Servicing operations performed on aircraft include refueling and recharging with oil, water, gases and chemical fluids. Extensive ground equipment and special machines are used for this.

Servicing operations are performed very frequently; therefore, special attention sould be devoted during design and production of aircraft on the possibility of reducing labor expenditures and time of performing these operations during maintenance. /166

The main requirements of the aircraft structure for servicing operations reduce to the following:

1. The connections and filler on aircraft and their ground service facilities should be manufactured according to international standards.

2. Convenient access during servicing should be provided for all recharging connections and fillers.

3. The aircraft fuel system should permit centralized refueling of the tanks from all refuelers and fuel-filling columns available at operational enterprises.

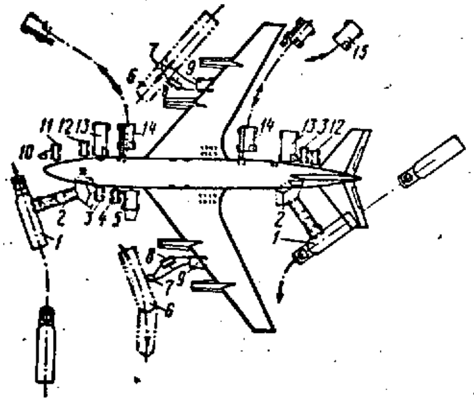

Figure 69. Diagram of disposition of ground equipment in servicing of the Boeing-707-430 aircraft:

1- passenger bus; 2- gangway; 3- water fillers; 4- air filler; 5- cabin air-conditioning facility; 6- fuel filler; 7 and 8- *; 9- measuring filtering installation; 10- distributor; 11- electrical apparatus; 12- special machine for cleaning sanitary facilities; 13- special machine for loading galley buffet; 14- baggage machine with belt conveyor; 15- loading machine.

4. The connections and fillers should be located so as to provide simultaneous operation of all the necessary complex of equipment near the aircraft, not only of the service, but also other equipment and special machines (Figure 69).

Inspection and Adjustment Operations

Periodic inspection and adjustment of many assemblies, apparatus and systems must be performed during operation of a modern transport aircraft. The reliability and operating lifetime of the aircraft systems depend on how timely and statisfactorily these operations are carried out. Tire pressure, the pressure in the shock-absorbing struts of the landing gear and brake system

*Translator's note: Missing in foreign text.

are usually checked during maintenance, the engine, rudder, aileron, flap and trim tab control are adjusted, many radio electronic and pilot navigation devices are tuned, etc.

Problems of providing convenient performance of inspection and adjusting operations on an aircraft during its design and manufacture are often forgotten, which subsequently leads to an increase of the cost of checks and labor expenditures. However, there are successful solutions deserving of attention on provision of easy access in performing inspection operations. Let us present some examples. /1

Thus, a dual filter with a filtering capacity of three microns is installed in the overflow line of each hydraulic system on the Fokker F-28 Fellowship aircraft. A telescoping button, which protrudes from the filter housing, emits a signal if the pressure in the filter drops below the permissible point. Ordinary high pressure filters with a filtering capacity of 25 microns are installed in each feed line. These filters are also equipped with telescoping signal buttons. If obstructed, the filter easily maintains total pressure in the system without breaking down. The pressure in the hydraulic system and the reservoirs of the main and emergency brake systems, and also the amount of fluid in each reservoir are indicated by indicators in the pilot cockpit. Moreover, the crew receives warning signals about low pressure at the output of one of the motor-driven pumps, about low air pressure in the reservoir and about overheating of the system.

The amount of fuel in the tanks of the F-28 aircraft during parking may be checked precisely with the aid of six magnetic level indicators and devices for determining the aircraft's position in pitch and roll. This device, which works on the principle of a bubble level, is installed in the compartment where the fuel feed regulation panel is located. There is also a table by which, knowing the fuel level in the tanks, the amount of fuel in them can be determined with an accuracy up to 1% for 49 positions of the aircraft (in pitch and roll).

A self-regulating system for checking and determination of failures FAST (Failure Annunciation and Self-Test) is used to inspect many apparatus of the L-1011 aircraft.

The electrical generators, in particular, may be checked using this system. If there is a malfunction in some generator bearing, a signal lamp lights up on the panel of the flight engineer. Failure of a malfunctioned bearing and breakdown of an apparatus are prevented by a redundant sliding bearing. The oil-lubricated sliding bearing provides no-failure operation of the generator for 14 hours, which exceeds by threefold the time that the L-1011 airbus is in flight.

When the RB-211 engine is stopped, the FAST system automatically checks all circuits within 10 seconds and indicates a malfunctioning circuit requiring replacement on the panel of the flight engineer [41].

The following requirements may be placed on an aircraft design in order to provide successful performance of checking and adjusting operations:

1. Apparatus which require periodic inspection during operation should have output devices for measurement of the determining parameters during maintenance without dismantling from the aircraft.

2. Apparatus which require continuous checking of their technical condition during operation of the aircraft should be monitored with the aid of automatic control systems.

3. The main power components of the aircraft, which limit prolonged reliable operation of individual assemblies, should be adapted to periodic inspection with the aid of physical non-destructive inspection methods during maintenance and repair.

4. Convenient access with a rather wide working area should be provided for the apparatus of aircraft equipment, subject to inspection, regulation and checking. /168

5. All apparatus, inside which are located regulating or protective devices (for example, remote resistors and fuses), should be located in zones provided with free and safe access during operation of the engines.

6. Connecting points (pipe connections, plug-and-socket connections etc.) for connecting power sources, inspection and measuring apparatus, and automatic control system apparatus to the aircraft should be standardized. The use of standardized instruments, apparatus, and attachments should be provided to perform inspection and adjusting operations.

Operations of Bracing Inspection

Many threaded connections of aircraft components gradually weaken in time due to the effects of variable loads, vibrations and other causes. If weakening of a thread is not detected in time, it leads to development of gaps between contiguous components, to their relative shifting and to development of dynamic loads, which in turn cause a progressive increase in the wear of components which often leads to their failure.

In order to prevent the development of this defect, operations of bracing inspection are performed periodically during maintenance of the aircraft, which include inspection of threaded connections from the outside and checking of their tightness with the aid of calibrated wrenches. Undetected weakening or insufficient tightening of the nuts of track bolts may lead to premature failure of individual assemblies and apparatus.

Access to the main threaded connections, the nuts of track bolts for connection of fuselage parts, the wing of the fuselage, the tailplane and vertical stabilizer of the fuselage, the pressurized floor of the fuselage etc. is usually difficult on many types of aircraft. Specific requirements should be observed during design and manufacture to increase the maintainability of aircraft structures. When establishing these requirements, one cannot be limited only to consideration of compulsory routine operations, provided by the maintenance regulations. Operations related to correction of all possible malfunctions, detected during maintenance, and also to replacement of assemblies and apparatus which have completed their established service life, should also be taken into account. On this basis, the requirements of the aircraft structure with respect to adaptability to operations of inspecting the bracing may be formulated in the following form.

1. Threaded connections which require periodic inspection and checking of the tightness of bolts should be easily accessible during aircraft maintenance.

Checking the tightness of bolts and performing strengthening operations during disassembly and assembly of apparatus and assemblies should be carried out without simultaneous use of a second instrument (wrench or screwdriver).

2. The system of fastening assemblies, apparatus and components, removed for checking or replaced during operation, should provide performance of fastening operations with minimum labor

expenditures. When selecting fastening components, norms and standards should be used to the maximum. The wrench sizes of bolt heads and nuts should be standardized. The total number of different sizes of strengthening components used on an aircraft should be a minimum.

3. Hatch covers, removed during maintenance, should be secured with reliable fast-response locks.

4. All fastening components of threaded connections should have stable anti-corrosion protection.

6. Providing Continuity of the Ground Maintenance Facilities

Classification of Ground Maintenance Facilities

Ground maintenance facilities include the equipment, with the aid of which are performed all types of aircraft maintenance (without measuring the parameters of the on board systems), and also storage of aircraft at the airfield.

These facilities come into direct contact or are connected to the aircraft and its systems during operation and consist of:

- ground equipment delivered centrally;
- ground equipment delivered together with the aircraft.

Ground equipment delivered centrally is mainly standard equipment which provides maintenance of several types of aircraft.

Ground equipment delivered with the aircraft consists of adapted and original equipment which is used in maintenance of basically one type of aircraft. The given group of ground maintenance facilities is delivered to operational enterprises in different combinations according to the stipulations of the contract and the existing standards.

Adapted equipment is understood as that which, being designed for maintenance of other types of aircraft, may also be used for maintenance of a given type of aircraft.

Original equipment is understood as that which was designed for maintenance of only one type of aircraft.

Ground maintenance facilities, delivered centrally, are divided into specific groups. Six such groups may be named: /170

1. Facilities for recharging the aircraft systems with fuel and lubricants, and technical fluids and gases.

2. Power supplies for the aircraft systems: electrical, hydraulic, pneumatic and combination.

3. Heat engineering facilities: air-conditioners, heaters, and ventilation installations.

4. Towing facilities: two trucks and universal towing and steering arms.

5. Transport lifting and installation facilities, and facilities which provide access (cranes, hoisting platforms, gangways, universal ladders and stairs, and carriages).

6. Cleaning and housekeeping facilities: washing machines, vacuum cleaners and special machines.

The ground equipment delivered together with the aircraft includes:

- towing and berthing facilities (towing and steering arms, cables, hold-down devices, support blocks, and berthing devices);
- devices which provide access to individual parts of the aircraft (stairs, ladders and platforms);
- hoisting devices (hoists, lifting jacks, safety blocks);
- facilities for disassembly and assembly of aircraft apparatus (extracting devices, assembly carriages, wenches, straps and crosspieces);
- facilities for maintenance of individual systems and apparatus (devices for filling, devices for preparation for storage and taking out of storage, overflow devices, lubrication devices, pumping devices, molds, cables, packing, hoses, and reducing pieces);
- devices for protecting service personnel and the aircraft during parking (hoods, mats, covers, end caps, screen, clamps, helmets, footgear, safety wires and belts).

This classification, without claiming to be final, may be recommended for use in development of specifications for new aviation materiel, when providing a given type of aircraft with the necessary ground equipment during its development, and also when determining the indicator of continuity of ground maintenance facilities.

Main Requirements

1. Ground maintenance facilities should be developed in order to provide:

- the minimum possible time of aircraft maintenance;
- a high level of operational reliability, service life and economy;

- convenience in operation with a minimum number of service personnel;
- safe and harmless working conditions.

2. The designs of ground maintenance facilities, delivered both centrally and together with the aircraft, should be standardized, i.e., they should be manufactured according to the specifications of existing All-Union and State Standards.

3. Ground maintenance facilities should be manufactured primarily from standardized assemblies and components and should be suitable for maintenance of several types of aircraft.

4. Lists of the original equipment, developed for maintenance of only a single type of aircraft, should be minimum.

5. The value of the indicator of continuity of ground maintenance facilities, calculated by formula (58), should be no less than 0.9 for a modern civil aviation aircraft.

6. When developing aircraft systems and ground maintenance facilities, the possibility should be provided of maximum use of facilities mass produced and which are already in operation in civil aviation enterprises.

7. Development of the Maintenance and Repair Documentation Delivered with the Aircraft

Successful solution of the problems of providing maintainability of aviation materiel and organization of maintenance and repair is also determined to a great extent by the completeness and quality of the maintenance and repair documentation, developed by the design offices and industrial plants. These include primarily: instructions on technical operation, repair manuals, spare parts catalogs, maintenance regulations and other documents.

The quality of developing maintenance and repair documentation and the timeliness of its delivery to the operational and repair enterprises affect the:

- periods and quality of training the service personnel;
- the periods of assimilation and introduction of new equipment into operation;
- an increase of the operational reliability and efficiency of aircraft utilization;
- improvement of the material and technical supply system.

An ever greater number of manufacturing firms of different countries have been guided in recent years by the ATA-100 (Air Transport Association) specifications in development of maintenance and repair documentation for aircraft, engines and finished articles.

The ATA-100 specifications for maintenance and repair documentation, delivered with the aircraft, coincide to a considerable extent with the specifications placed on the same type of documentation by specialists of operational civil aviation enterprises in the Soviet Union. Therefore, it makes sense to briefly outline the contents of the main specifications. /1

It should first be noted that maintenance and repair documentation for all types of aircraft acquired a single form and a unified clear order in outlining the material with the publication of the above-mentioned specifications, which considerably facilitates its use in operation, maintenance and repair.

For example, ATA-100 contains requirements for all published documentation related to maintenance and repair of aviation materiel, including sets of articles, in order to provide efficient and economic operation of it. The form, style and volume of the material, governed by ATA-100, correspond to the interests of the organizations which operate aviation materiel. The standard digital system, proposed by the specifications, provides the possibility of rapid retrieval of the most specific data on questions of interest.

The form of accounting for the regular changes in the documentation and the system of introducing changes and supplements, provided by the ATA-100 specifications, constantly ensure agreement between the technical condition of the aircraft (with consideration of modifications performed) and the documentation for its maintenance and repair. For convenience in the initial use of each of the books of maintenance and repair documentation, it is recommended that a list of chapters be given with an indication of the chapter's number and an index for each of them.

Thus, the first 12 chapters of the specifications contain general instructions on supplementing the main data on the aircraft, and on towing, steering, berthing, leveling and weighing.

Chapters 20 through 80 contain requirements for outlining material on operation, maintenance and repair of one of the aircraft systems. For example, Chapter 20 — "Airframe," Chapter 21 — "Air-Conditioning," Chapter 22 — "The Automatic Pilot" etc. When outlining the materials on technical operation of a system, all the necessary data on the apparatus, instruments and articles contained in the given system are also included.

In order to facilitate retrieval of the necessary material, a specific system of dividing the material inside any chapter and numerical notation of it is recommended. The following system is used for denoting the pages.

The code and number of the page is given in the lower outside corner of each page. The code consists of three groups of figures, separated by lines:

- the first and second figures are the chapter (system);
- the third and fourth figures are the section (subsystem);
- the fifth (sixth) figures are the subsection (apparatus).

For example, the code 52-30-2 denotes: Chapter 52 "Doors," /1
30 — the section "The Cargo Compartment Doors," and 2 — the subsection "The right front door of the cargo compartment." The page number is placed underneath the code, corresponding to the nature of the outlined material. Thus, the following pagination is used in the maintenance manual for individual sections:

Sections	Pages
Description, purpose, operation.	.1-100
Finding and correcting malfunctions.	.101-200
Maintenance.	.301-400
Disassembly and assembly	.401-500
Fabrication and testing.	.501-600
Acceptance and checking.	.601-700
Cleaning and painting.	.701-800
Routine repair	.801-900

The date of its issue is placed in the lower inner corner of every page.

According to the ATA-100 specifications, the developing firm should submit to the operating enterprise, prior to delivery of the aircraft or together with it, a set of the maintenance and repair documentation which includes the following: maintenance manual, major overhaul manual, an illustrated catalog of spare parts, electrical circuit manual, repair organization manual, list of instruments and equipment, operational bulletins, major overhaul manual of subcontractor articles, loading and centering manual, maintenance regulations, and flight operations manual.

The maintenance manual consists of a description and instructions on performing all types of operations which may be carried out on the aircraft, including replacement of apparatus and components. The material is outlined in the following sequence: description, purpose, operation; finding and correction of malfunction; maintenance; disassembly and assembly; fabrication and testing; inspection and checking; cleaning and painting; routine repair.

The major overhaul manual contains materials on repair of structural elements, but not of apparatus and components. Problems of apparatus and component repair are considered in separate manuals.

A repair manual for each of the apparatus and components of the aircraft consists of the sections: disassembly, cleaning, flaw detection, repair, fabrication, adjustment, testing, storage, instruments, tools and equipment. All sections are outlined with sufficient completeness for practice, with illumination of all the necessary data, specifications and norms of technical parameters (NTP).

It should be noted that formulation of materials on all assembly articles of the subcontracting firm is also carried out /174
strictly according to ATA-100. This makes it very convenient for the operational enterprises to use the documentation.

As operational experience is accumulated, all developers enter the necessary changes and supplements into the documentation by replacement of individual sheets in the books. The maintenance and repair documentation as a whole is usually not reissued and is the working documentation over a long period of time of operating the aircraft. This procedure of development and improvement of maintenance and repair documentation is very progressive. It greatly simplifies and expedites the work of the operational enterprises in assimilation and introduction into service of new types of aircraft with the least expenditures for facilities, and also facilitates the work of the enterprises at all subsequent stages of operation of individual articles and of the aircraft as a whole.

Each of the books of the manual or instructions has a list of pages which is scanned each time changes are introduced into the text of the document. The changes are issued usually no more than once per quarter. However, changes and supplements to the maintenance and repair documentation may be introduced more often for new types of aircraft.

At the present time a number of foreign and Soviet aircraft have maintenance and repair documentation compiled according to the requirements outlined.

8. Compilation of Maintenance Regulations During Development of an Aircraft

The basic document which determines the volume and frequency of maintenance operations on an aircraft during its operation is the maintenance regulations. Such indicators as operational reliability and the extent of utilization, as well as operating expenses, depend to a large extent on how correctly the regulations reflect the requirements of the aircraft structure, individual systems and apparatus for preventive measures according to the number of hours of accrued flight time.

The maintenance regulations are worked out by the specialists of the design offices during development of the aircraft. With further operation of the aircraft, the regulations are continuously corrected and improved on the basis of data from analysis of its technical condition. In this case, the main purpose is to provide strict agreement of the regulations with the actual technical condition of the aircraft and its requirements for preventive maintenance at each stage of operation.

Many years of practice have demonstrated that operations to correct regulations are more successful, the more accurate is their initial variant, to be tested together with a new type of aircraft. Therefore, the task of developing initial maintenance regulations for a new type of aircraft, /175
reflecting more fully its requirements for preventive maintenance, is very timely. At the same time this problem is extremely complicated.

When developing maintenance regulations for a new type of aircraft, a number of problems related to determination of the initial list of maintenance operations, the frequency of performing each of them, the expected labor expenditures, and the number of periodic forms of maintenance, must be solved simultaneously. At the given stage, the problem of grouping individual maintenance operations into optimum forms of regulations, used for the aircraft as a whole, is also resolved.

As indicated by investigations, solution of all the enumerated problems during the development stages of the aircraft may be greatly facilitated if the so-called standard regulations are used when working on compilation of the initial regulations.

The standard regulations are developed on the basis of extensive analysis of the maintenance regulations, existing in civil aviation enterprises, for five main types of gas turbine aircraft and are recommended for use in all leading design offices.

Classification of regulation work, according to which the standard regulations were developed, is presented in Table 30. This classification is recommended for utilization in development of initial regulations for new types of aircraft.

TABLE 30. /17

Name of operation: Group	Name of operation: Subgroup	Purpose or reason for performance	Code
	I. Flaw detection operations		
1. Inspection	1. External inspection of maintenance object without use of inspection facilities	Checking for the absence of impermissible damages, * contamination and traces of leaks of fuel and oil, special fluids, and of and contaminants	111
	2. Inspection of the maintenance object using additional inspection facilities	Checking for the absence of impermissible damages and checking for the agreement of NTP	112
2. Checking the parameters of the condition of the maintenance objects	1. Checking the parameters of the maintenance object without use of additional inspection facilities	Determination of clearances and play in connections, wear and sagging of wire antennas etc.	121

*Damage is understood as any deviation of parameters of the considered maintenance object from the established norms.

Name of operation		Purpose or reason for performance	Code
Group	Subgroup		
	2. Checking of the parameters of the maintenance object using additional inspection facilities	Determination of clearances and play in connections, wear of cables, value of insulation resistors etc	122
	3. Checking of the parameters of the maintenance object using automatic control systems	Checking for compliance with predicted NTP parameters	123
3. Checking the functioning and operating parameters of maintenance objects	1. Checking the functioning of the maintenance object without measurement of parameters	Determination of the functioning of the maintenance object	131
	2. Checking the efficiency without use of additional inspection facilities	Checking for conformity of NTP	132
	3. Maintenance and checking of efficiency using additional inspection facilities	"	133
	4. Checking of efficiency using automatic control systems	"	134
II. Refueling and lubrication operations			
1. Inspection of the working body and its characteristics	1. Draining of fuel and oil residue and special fluids	Checking of the physical condition of fluids	211

Name of operation		Purpose or reason for performance	Code
Group	Subgroup		
	2. Checking the presence of the working body without measuring the parameters	Checking for the conformity of NTP	212 /1
	3. Checking and quantitative analysis of the working body without using additional inspection facilities	Checking for conformity of NTP	213
	4. Checking and quantitative analysis of the working body using additional inspection facilities	"	214
2. Supplementing the working body reserves	1. Lubrication operations	Restoration or replacement of lubricant	221
	2. Replacement of fuel and oil and special fluids upon completion of operating life	Restoration of initial characteristics	222
	3. Filling with fuel and oil, water, special fluids, and recharging of gases and reservoirs.	Bringing into conformity with NTP	223
III. Operations on cleaning and washing			
1. Removal of contaminants	1. Removal of contaminants without washing the maintenance objects	Restoration of the given parameters	311

Name of operation: Group	Subgroup	Purpose or reason for performance	Code	
	2. Washing of objects during maintenance	Restoration of the given parameters	312	
	3. Drying of maintenance objects	Removal of moisture or liquids used in washing	313	
	4. Finishing with a vacuum cleaner	Restoration of the given parameters	314	
	5. Chemical cleaning, disinfection and antistatic treatment	"	315	
2. Removal of accumulated liquids	1. Draining of condensate and accumulated liquids	Providing normal conditions of functioning of maintenance objects	321	

IV. Restorative operations

Group	Subgroup	Purpose or reason for performance	Code	
1. Fastening	1. Restoration of required tightness of fastening connections	Bringing into conformity with NTP	411	
2. Adjusting	1. Restoration of parameters of maintenance objects	Bringing into conformity with NTP	421	
	2. Restoration of operating characteristics of maintenance objects	Bringing into conformity with NTP	422	/178
3. Repair	1. Restoration of the integrity of maintenance objects	"	431	
	2. Restoration of paint and varnish coatings, removal corrosion, repair of inner skin of aircraft, seats etc.	Restoration of given parameters	432	

Name of operation		Purpose or reason for performance	Code
Group	Subgroup		
4. Disassembly and assembly	1. Replacement of aparatus or their elements which have completed their operating life	Restoration of the initial characteristics in the replaced apparatus	441
	V. Auxiliary operations		
1. Providing access to maintenance objects (opening of hatches, panels, fillets, protective bands etc.)	—	Creation of necessary conditions for performing maintenance	A
2. Hoisting and supporting of aircraft	—	Providing possibility of performing maintenance	B
3. Draining or filling with fuel and oil, water, and pressurizing the special fluids and gases in the systems	—	"	C
4. Cleaning the objects of contaminants prior to maintenance	—	Preparation of maintenance objects for flaw detection, application of paint coating, lubrication etc.	D
5. Disassembly and assembly operations for performing maintenance	—	Performing maintenance of objects outside aircraft	E

According to the given classification, all maintenance operations are divided into five types: flaw detection; refueling and lubrication; cleaning and washing; restorative; and auxiliary operations. In turn the operations of each of the enumerated types are divided into groups as a function of the extent of inspection of the condition of the maintenance objects and of their working parameters, and also of the labor expenditure of performing them and the complexity of the technical inspection facilities used, and each group is divided into subgroups.

Each type of aircraft is divided into systems, functional subsystems and typical assemblies, which include the maintenance objects, in order to compile lists of standard regulations. Either individual apparatus or a part or group of them, and in a number of cases the subsystem or system of the aircraft as a whole, were separated as a function of the nature of the work performed on the maintenance object. The regulation operations are scheduled strictly according to the maintenance object for each aircraft system.

After analysis of operations on similar objects of all considered aircraft, the summary results are recorded in a common table, an example of the formulation and supplementing of which is presented in Table 31.

As a result, the entire complex of operations which must be performed in accordance with different regulations was determined for each maintenance object.

Compilation of the list of standard maintenance operations /179
was carried out with consideration of the following factors:

- the frequency of performing the considered operation on similar maintenance objects of different types of aircraft;
- the prospects for development of different systems and maintenance objects of aircraft;
- the effect of the operations included in the list on flight safety.

TABLE 31.

Maintenance object	Operation performed	Purpose of performing operation	Frequency of performing operations on aircraft, hours of accrued flight time								
			IL-18	An-10	An-24	Tu-114	Tu-104	Tu-124	Tu-134	IL-62	YaK-40
I. Power plant											
Oil system											
Oil tank	External inspection	Determination of pressence of cracks, dents, deformations, weakening of fastenings, oil leaks etc.	50	50	50	50	50	50	50	50	50
	Measurement of quantity of oil	Checking of conformity to NTP	50	50	50	50	50	50	50	50	50
	Flushing of filter seives and inspection	Removal of contaminants, checking for absence of damage	200	200	1200	—	—	—	—	—	—
	Disassembly, washing, inspection and assembly	Cleaning of contaminants, checking for absence of damage	1000, engine replacement	1000,	1200,	—	engine replacement	PTO	1000-1500	—	—
	Testing for hermeticity	Checking of conformity to NTP	—	—	—	—	—	PTO	—	—	—
Drainage of tank	External inspection	Ascertaining the absence of cracks, dents, wear and reliability of fastening	—	50	50	—	—	—	—	—	—
	Disassembly, washing, inspection and assembly	Cleaning of contaminants, checking for absence of damage	Engine replacement	—	1200, engine replacement	—	—	—	—	—	—

A unified enumeration of aircraft systems and subsystems, identical formulations for identical operations, and common code notations for operations are given in the list of standard maintenance operations. Encoding of the operations is accomplished with the aid of numerical and letter notations (see Table 30). The first figure of the code denotes the type of operation, the second — the group of operations in the considered form, and the third — the subgroup of operations in the considered group. The letter notations are used only to encode groups of auxiliary operations. This makes it possible to more clearly separate the main operations from the total aggregate of maintenance operations.

Let us consider as an example encoding of operations performed during maintenance of the oil filter at the engine input. These operations include: disassembly of the oil filter for servicing and its assembly, code — E; external inspection of the filter for determining the presence of metal particles and damage, code — 111; flushing of the filter to remove contaminants, code — 112. Therefore, all operations on servicing of the filter are denoted by the code — 111, 312E.

The recommended form of the list of standard regulations and an example of supplementing it are presented in Table 32.

The operations which are not included in the given list should be related to non-standard operations. It should be noted that non-standard operations are presently carried out on all existing types of aircraft and, undoubtedly, will be included in regulations for new types of machines. However, introduction of each of these operations into the regulations in the future will require justification with indication in a number of cases of the period after which the frequency of performing the operation will be increased or that the operation will be eliminated from the regulations.

TABLE 32.

Classification number	Name of system, subsystem or article	Zone	Content of operations	Code of operation	Purpose of performing operation	Frequency achieved, hours of accrued flight time
21	Air-conditioning system					
21-00-00	Common part					
21-01-00	Pipelines and apparatus of system		External inspection at access points without using special inspection facilities	111	Checking for the absence of impermissible damage and for the reliability of fastening	1200
21-02-00	Pressurized part of fuselage		Checking of the parameters which characterize the condition of the fuselage using additional inspection facilities	122	Checking of fuselage pressurization and for absence of protrusion of cabin glass	1200
21-10-00	Air delivery					
21-10-01	Fuel lines from engine to pressure flaps		Checking of the parameters which characterize the state of the pipelines using additional [illegible]	122	Checking for sealing	PTO

The recommended frequency for performing each of them is also indicated in the list of standard operations. The frequency of performing similar operations on most types of aircraft, achieved at the present time, is accepted as the recommended frequency. When developing regulations for new types of aircraft, the scheduled frequency for each of the operations should be no less than that recommended in the list.

9. Organization of Operations to Provide Maintainability

Consideration of the problem of providing maintainability of an aircraft structure during its development will be incomplete if we do not dwell on certain aspects of organizing the performance of this extensive and complicated operation.

As indicated by practice, clear organization of the operation /182
in solving the problem of maintainability is necessary, primarily, in conducting investigations to develop specifications and recommendations, and also in implementing the developed specifications into the aircraft designs created for civil aviation. In this case it should be noted from the very beginning that successful solution of the posed problems may be counted on only in those cases when specialists of design offices and industrial plants, scientific and research organizations, and also operational and repair enterprises of civil aviation are intimately involved in such work.

The entire complex of research on providing maintainability of aircraft may conditionally be divided into three stages (Table 33).

The first two stages of the operations are related to gathering of the required data, analysis and classification of the materials

TABLE 33.

Analysis and classification of materials on maintainability	Materials on maintenance and repair of the aircraft of the main fleet
	Materials on maintenance of the leading aircraft and aircraft of the first in a series
	Materials on testing of new types of aircraft
	Materials on foreign aircraft, their maintenance and repair
Development of technical guidelines on maintainability	Requirements for modification of the designs of existing types of aircraft
	General requirements on maintainability of new types of aircraft
	Indicators, methods of calculation and analysis of maintainability
Control over performance of maintenance and repair and analysis of the level of maintainability	During development of aircraft
	During testing of aircraft
	During operation of aircraft

obtained, and also development of the necessary technical guidelines (RTM) on maintainability.

The third stage of operations includes exercising control over performance of RTM and analyzing the maintainability level at different stages of development aircraft and testing them.

Let us consider the main content and organization of operations at each of the stages.

Exhaustive initial data are required during the first stage of the investigations to analyze and classify the materials. Gathering the required initial data is carried out primarily by direct separate observations of each system, assembly or apparatus installed on different types of aircraft, during their maintenance and during major overhaul.

Materials on maintainability are also collected while performing "in-depth" flaw detection and inspection of aircraft, included in the so-called command groups. The aircraft of command groups are operated with advance flights and an increase of the repair cycle as compared to ordinary scheduled aircraft, and as a result of this, a number of operations on repair and replacement of apparatus and assemblies, which are usually not performed on scheduled aircraft, are performed on them after a specific accrued flight time.

In a number of cases valuable data on the technological effectiveness of designs are received from enterprises and specialists, conducting factory, state and field tests of new types of aircraft.

Finally, data are collected on the maintainability of foreign aircraft designs, and methods and techniques of maintaining and repairing them.

According to the results of analysis and processing of the factual data obtained during the second stage of investigations, the design offices and industrial plants develop and issue such necessary technical guidelines as: /18

- measures to increase the maintainability of serially-produced aircraft by performing the appropriate design modifications on them;
- general specifications on provision of maintainability of new types of aircraft;
- quantitative indicators, methods of calculation and analysis of maintainability;
- recommendations for designers concerning maintainability which contain data on rational variants of individual design, and technological solutions which satisfy the given specifications.

The main volume of work on the first two stages of the investigations is carried out by the customer: specialists of scientific and research organizations, and operational and repair enterprises of civil aviation. The specialists of design offices and industrial plants participate in the work, but their participation is reduced mainly to consideration and coordination of the prepared materials.

Organization of work on the third stage, related to implementation of the specifications adopted in the designs of the aircraft being developed, is characterized by the following.

First, the condition that maintainability be provided during development of a new parts just like aerodynamic, strength, weight and other indicators, with subsequent careful inspection during official and field tests, is compulsory.

Secondly, provision of maintainability is accomplished at all stages of designing the aircraft, beginning with preliminary design, when the architecture of the aircraft is being determined and when all essential problems of configuration, connections, wiring etc. are being resolved.

Third, the entire collective of designers and technologists of both the aircraft design office and of the plant, and of design offices and plants which are developing finished parts for the aircraft, participate in work on providing maintainability.

The basis of design and manufacture of more improved aircraft is scientific generalization of operational experience. Constant study and generalization of the operational requirements on aircraft, and also the available design deficiences, in order to eliminate them during development of new machines is the most important problem faced by the designers and engineers. When solving this problem, the designers may be assisted considerably by the operational workers who have the necessary data on the design and production defects of aircraft assemblies and systems. /185

During the third stage of the investigations, unlike the first and second, all operations are performed by the developer: specialists of design offices and industrial plants. The role of the customer representatives is reduced to exercising control over fulfillment of the specifications, consideration and coordination of the main design and technological solutions, and necessary consultations with the designers.

The participation of the customer representatives in the work of the third stage is formulated organizationally in the following manner.

Highly qualified operational specialists, familiar with the fundamentals of design and manufacture of aircraft and who have a good knowledge of their maintenance and repair, are sent to the design office during the development of a new type of aircraft. Teams of such specialists work in the design offices. Their main tasks, as already noted, are to supervise the fulfillment of the customer's specifications for maintainability and to give necessary and timely advice to the designers. The team members specialize in one or two systems during the work. Having all the necessary data at their disposal, they take an active part in the technological development of the design being developed, and also in the design solutions in dividing the airframe into apparatus, the apparatus into panels and assemblies, finishing of wiring, configurations and connections and other problems.

Available data from foreign companies about the participation of airline company representatives in providing maintainability of aircraft, confirm that they solve this problem in a similar manner.

Thus, English airline companies have groups of their own specialists at each aircraft company. During development of the Trident aircraft, for example, a group of experienced specialists of BEA were sent on temporary duty to the Hawker Sidley Firm since this airline company was the first and main customer for the aircraft. The specialists of the airline company, besides exercising control over fulfillment of the given specifications by the firm, participated in solution of individual problems related to development of a design which would require minimum labor expenditures for maintenance and repair.

Summarizing the foregoing, organization of work on increasing the maintainability of aircraft may be represented schematically in the following manner.

1. Extensive investigations, analysis and classification of materials on maintainability of the designs of existing types of Soviet and foreign aircraft should be carried out through the efforts of specialists of design organizations, industrial scientific research institutes and operating organizations. The /186
design and production solutions of individual assemblies, connections, configurations, joints etc. should be carefully analyzed, labor expenditures for maintenance and repair and expenditures (in rubles) for materials and spare parts should be calculated in order to develop specific proposals to increase the maintainability of mass-produced aircraft.

2. Taking into account accumulated operational experience, work must be continuously carried out to improve the specifications and recommendations on providing maintainability of aircraft in order that the requirements at each stage of development of civil aviation reflect the level of the best worldwide advances.

3. Work should be carried out on compilation of recommendations for designers of aircraft maintainability, containing a minimum of basic data which are required for providing a high level of maintainability of the designs being developed.

4. Technological completion of designs should be carried out with the participation of operational specialists during the period of designing new types of aircraft. Control over fulfillment of the requirements for maintainability of the aircraft should be provided at the stages of preliminary, technical, and operational design.

5. Calculation of indicators and analysis of the level of maintainability of an aircraft during testing and operation should be carried out strictly in accordance with the existing inter-agency procedures. Development of special procedures is required to

perform similar calculations and analyses when developing the aircraft and its systems.

Far from all the requirements for maintainability which a modern transport aircraft should satisfy, and only some of the possible methods of increasing maintainability, have been considered in the present chapter. Soviet aircraft must differ considerably from foreign aircraft due to the fact that their operational cost in the broadest sense of this word should be at a minimum with the greatest safety, speed and comfort of passenger transport. This may be achieved only by close cooperation between the designers, engineers and operating personnel during design and manufacture of the aircraft, and also during their operation.

There is no doubt that the present investigations, aimed at solving the problem of maintainability, will lead to further improvement of the designs. In the development of new types of transport aircraft, the requirements for maintainability will be regarded as basic requirements and will be satisfied by the designers when the designs are initiated.

C-4

APPENDIX

Appendix 1

Recommended Values of the Coefficient of Assessibility K_a and Time Required for Replacement of Certain Parts of Gas Turbine Aircraft

Type of operation	Value of K_a	Total time for performance of operation, hours and minutes
Airframe		
Replacement of rudder	0.9	2.00
Replacement of elevator (one-half)	0.9	1.00
Replacement of aileron	0.9	2.00
Replacement of training-edge flap	0.7	1.30
Replacement of wing leading edge	1.0	2.00
Replacement of vertical stabilizer	1.0	1.00
Replacement of wing tip	1.0	0.30
Replacement of vertical stabilizer fairing	1.0	0.20
Replacement of tailplane fairing	1.0	0.20
Replacement of radar antenna cone	1.0	0.20
Replacement of wing-to-fuselage fillet	1.0	2.00
Replacement of baggage compartment hatch cover	1.0	0.40
Replacement of glass in window of passenger cabin	0.8	0.20
Opening and closing of a single cover of an operational access hatch	1.0	0.05
Power plant		
Replacement of engine (without run-up and flight of the aircraft)	1.0	2.30
Replacement of aircraft fuel pump	0.7	1.00

Nomenclature of operation	Value of K_a	Total time for performance of operation, hours and minutes	
Replacement of oil tank	1.0	0.30	
Replacement of oil cooler	1.0	0.45	
Disassembly and assembly of aircraft fuel filter	1.0	0.10	
Disassembly and assembly of oil filter	1.0	0.10	/188
Replacement of generator	1.0	0.30	
Replacement of starting unit	1.0	0.30	
Replacement of propeller	0.8	0.40	
Replacement of wind-vane pump	1.0	0.30	
Aircraft and engine controls			
Replacement of one of the control thrusters	0.8	0.20	
Replacement of the transmission shaft for the trailing-edge flap	0.8	1.00	
Replacement of the control thruster pressure lead	0.67	1.30	
Replacement of the cable run element on the section between the sealing assemblies	0.9	0.20	
Replacement of the steering mechanism (ailerons, elevator and rudder)	0.75	0.30	
Replacement of the bearing for the elevator, rudder and aileron suspension support	0.3	3.00	
Replacement of the bearing for the trim tab and servocompensator suspension support	0.3	1.00	
Lubrication of the movable connections of the pressure leads	0.9	0.10	
Lubrication of all articulated connections of the control system	0.8	1.00	
Measurement of the tension of one element of the cable run	0.9	0.02	
Replacement of the guide rollers in one assembly	0.9	0.35	
The landing gear and hydraulic system			
Replacement of the front landing gear leg	1.0	4.00	
Replacement of the main landing gear leg	1.0	5.00	

Nomenclature of operation	Value of K_a	Total time for performance of operation, hours and minutes
Replacement of the wheel of the front leg	1.0	0.15
Replacement of the wheel of the main leg	1.0	0.20
Replacement of the front landing gear retraction and extension cylinder	1.0	0.30
Replacement of the main landing gear retraction and extension cylinder	1.0	0.40
Replacement of the carriage damping cylinder (the stabilizing shock absorber)	1.0	0.30
Renewal of lubricant in the articulated assemblies of the landing gear	1.0	0.30
Renewal of lubricant in the articulated connections and mechanisms of the landing gear doors	1.0	0.10
Replacement of the hydraulic system tank	0.9	0.50
Drainage tank on the hydraulic system	0.9	0.25
Replacement of the hydraulic pump on the engine	1.0	0.30
Replacement of the hydraulic reservoir	1.0	0.30
Disassembly and assembly of the hydraulic system filter	1.0	0.20
Disassembly and assembly of the hydraulic panel having 8-12 apparatus	1.0	1.00
Replacement of the automatic pressure device	1.0	0.30
Replacement of the break valve	0.8	1.00
Replacement of the distributor damping mechanism	0.7	1.30
Replacement of the control cylinder	1.0	0.30
<u>High-altitude equipment</u> /189		
Replacement of the atmospheric-air cooler	0.8	1.30
Replacement of the turbine cooler	0.7	0.45
Replacement of the pressure regulator	0.7	0.30
Replacement of the slide valve	0.7	0.25
Replacement of the absolute pressure limiter	0.9	0.30
Replacement of the throttle	0.8	0.20
Replacement of the flap cover unit	0.9	0.30
Replacement of the reverse valve	0.86	0.30
Replacement of the box for individual cabin ventilation or heating line	0.67	0.40

Nomenclature of operation	Value of K_a	Total time for performance of operation, hours and minutes
<u>Electrical equipment</u>		
Replacement of the set of brushes of one generator	0.9	0.30
Replacement of the converter	0.85	0.15
Disassembly and assembly of the voltage regulator	0.9	0.10
Disassembly and assembly of the circuit breaker	0.9	0.10
Replacement of one light fuse	0.9	0.05
Disassembly and assembly of one light	1.0	0.10
Replacement of the bulb in a light	0.8	0.05
Replacement of the electrical mechanism of the heating valves	0.9	0.15
Replacement of the set of brushes of the current collector on the propeller	0.8	0.20
Checking and adjustment of the glass heating	1.0	0.10
Replacement of the electrical mechanism of the trim tab control	0.9	0.20
Replacement of the electrical mechanism of the rudder stop	0.9	0.20
Adjustment of trailing-edge flap release	0.95	0.40
Replacement of storage batteries	0.9	0.10
<u>Cabin equipment</u>		
Opening and closing of one of the ceiling panels	1.0	0.05
Replacement of the floor panels in one of the toilet compartments	0.8	1.00
Replacement of the water tank	0.75	1.00
Replacement of the chemical liquid receiving tank	0.8	2.30
Replacement of the pump for the chemical liquid receiving tank	0.8	0.30
Replacement of the chemical liquid filter for the receiving tank	0.9	0.20
Replacement of the seats of the crew members (any one)	1.0	0.10
Replacement of one of the passenger seats	1.0	0.15

Nomenclature of operation	Value of K_a	Total time for performance of operation, hours and minutes
Radio equipment		
Replacement of the RLS* radar transeiver	0.9	0.30
Replacement of the RLS radar scope	1.0	0.20
Replacement of the UHF radio station UKV	1.0	0.15
Replacement of the communications transmitter	1.0	0.20
Replacement of the communications receiver	1.0	0.15
Replacement of the radio equipment unit	0.9	0.30
Replacement of the display device	1.0	0.20
Replacement of the ARC directional antenna	0.9	0.25
Replacement of the HF cable from the antenna to the component	0.8	0.40
Instrumentation		
Replacement of the automatic fire extinguishing unit	0.8	0.10
Replacement of the fire extinguisher warning signal	0.9	0.15
Checking and adjustment of the course system	1.0	0.30
Disassembly and assembly of one hydraulic unit	0.8	0.10
Replacement of the course sensor	1.0	0.10
Checking and adjustment of the astrocompass	1.0	0.20
Replacement of the amplifier for the course system or the astrocompass	0.8	0.15
Replacement of the apparatus for the pilot-navigator system	0.95	0.25
Replacement of the automatic pilot controls	0.8	0.20
Replacement of one thermocouple unit (four pieces)	0.9	0.20
Replacement of the temperature indicator	0.7	0.15
Checking and adjustment of the temperature indicator unit	0.95	0.20
Replacement of the aneroid membrane device	0.9	0.15

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* Translator's Note: This designates radar station.

Appendix 2

List of Some Ground Maintenance Facilities, Which Are Centralized and Used at Civil Aviation Enterprises

Nomenclature	Brief Characteristics	
	Facilities for refueling with fuel and oil, special fluids and gases	
TZ-22 refueler	Capactiy of tank, liters	20,000
	Productivity, liters/minute	1,500
	Pressure in the delivery system, kg/cm^2	to 3.5
TZ-16 refueler	Capacity of tank, liters	16,000
	Productivity, liters/minute	840
	Pressure in delivery system, kg/cm^2	to 3.5
TZ-200 refueler	Capacity of tank, liters	7,000
	Productivity, liters/minute	400
	Pressure in delivery system, kg/cm^2	to 3.5
AMZ-53 oiler	Number of tanks	3
	Capacity of each tank, liters	30
	Productivity of filling, liters per minute:	
	oil	10
	AMG-10	17
	starting fuel	24
MZ-51M oiler	Capacity of tank, liters	850
	Productivity of system, l/min.	175
	Pressure in the sleeve, kg/cm^2	2
MZ-150 oiler	Capacity of tank, liters	2,100
	Productivity of system, l/min.	210
	Pressure in sleeve, kg/cm^2	to 2.5
A-33M universal filler	Capacity of tanks, liters:	
	for BZ-70	500
	for AMG-10	160
	for oil mixture	720
	for oil	530
	Number of tanks:	
	compressed air	4
	compressed nitrogen	3

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Nomenclature	Brief Characteristics	
MM-ZIL-130 water filler	Capacity of tank, liters	2,950
	Maximum pressure after pump, kg/cm^2	80
AKZS-40 oxygen charging station	Performance, m^3/hr	40
	Operating pressure, kg/cm^2	150
	Oxygen reserve, m^3	90
AKZS-75 oxygen recharging station	Performance, m^3/hr	75
	Operating pressure, kg/cm^2	150
	Oxygen reserve, m^3	100
VZ-20 air recharger	Number of tanks per machine	20
	Capacity of one tank, liters	40
	Number of tank groups	5
	Operating pressure, kg/cm^2	from 0 to 320
	Power sources	
APA-35-2M electrical unit	Output, kw	34
	DC voltage, V	28, 5-70
	Nominal current, a	600-1,200
	Type of converter	PO-4,500
	Voltage, V	115
	Frequency, Hz	400
APA-2MP electrical unit	Output, kw	17
	DC voltage, V	28.5
	Nominal current, a	600
	Type of converter	PO-4,500
	Voltage, V	115
	Frequency, Hz	400
AMGA-17 electrical unit	Output, kw	17
	DC voltage, V	28.5
	Nominal current, a	600
	Type of converter	PO-3,000
	Voltage, V	115
	Frequency, Hz	400
APA-50 electrical unit	Output, kw	50
	DC voltage, V	28.5
	Three-phase AC voltage, V	208
	Single-phase AC voltage, V	115
	Frequency, Hz	400
PPCh-1 electrical unit	Output, kw	30 /192
	Voltage, V	208
	Frequency, Hz	400
Universal hydraulic unit	Pressure at output, kg/cm^2	0-250
	Performance, liters/minute	15-85
	Working fluid	AMG-10

Nomenclature	Brief Characteristics	
UPG-250M mobile hydraulic installation	Operating pressure at output, kg/cm^2	50-250
	Performance, liters/minute:	
	with operation of one pump	40
	with operation of two pumps	70
	with operation of three pumps	110
	Working fluid	AMG-10
KND-1 compressor	Performance, m^3/hr	1,000
	Pressure at output, kg/cm^2	0.4
KND-3 compressor	Performance, m^3/hr	2,000
	Pressure at output, kg/cm^2	0.45-0.8
	<u>Heat engineering facilities</u>	
AKV-30/120 airport air-conditioner	Cold performance, kcal/hr	30,000
	Calorific capacity, kcal/hr	120,000
	Exhaust air temperature, °C:	
	during heating	to 80
	during cooling	+5-+10
MP-300 engine heater	Calorific capacity, kcal/hr	300,000
	Exhaust air temperature, °C	$\ngtr 130$
	Number of hoses	5
MP-85 engine heater	Calorific capacity, kcal/hr	88,500
	Exhaust air temperature, °C	$\ngtr 130$
	Number of hoses	2
MPM-85K engine heater	Calorific capacity, kcal/hr	85,000
	Exhaust air temperature, °C	$\ngtr 130$
	Number of hoses	2
PP-85 portable heater	Calorific capacity, kcal/hr	60,000
	Exhaust air temperature, °C	$\ngtr 130$
	Weight of heater, kg	40
	<u>Towing facilities</u>	
YaAZ-214 tow truck	Tractive force on hook, tons	14
	Weight, tons	19.5
MAZ-541 tow truck	Tractive force on hook, tons	20
	Weight, tons	34.5
	<u>Transport hoist and assembly facilities</u>	
K-51 hoisting crane	Load capacity, tons:	
	with a boom of 7.5 m	5
	with a boom of 12 m	3

Nomenclature	Brief Characteristics	
	Height of lift of hook, m:	
	with a boom of 7.5 m	7
	with a boom of 12 m	11
Crane on the chassis of the 4017 truck	Lifting capacity, kg	1,500 /193
	Height of lift, m	7.3
	Travel of hook along boom, m	1.7
	Lateral travel of boom with hook, m	±0.2
SPO-15M self-propelled maintenance platform	Lifting capacity, kg	300
	Maximum height to floor of working platforms, m	14.6
	Maximum sweep of boom, m	12.6
RL-12 extension ladder	Load capacity, kg	150
	Maximum height of lifting of platform, m	12
TS-8 telescoping ladder	Load capacity, kg	120
	Maximum height of lift of platform, m	8
Step ladder for working on engine	Height of platform, m	2.8
	Width, m	1.25
Step ladder for servicing wing and fuselage	Height of platform, m	3.6
	Width, m	0.6
Step ladder for covering aircraft	Height of platform, m	5.4
	Width, m	2.0
	Load on platform, kg	270
Universal wheel remover	Load capacity, kg	750
	Height of lift, m	1.6
Cleaning, washing and housekeeping facilities		
MMM-1 mechanized washing machine	Maximum height of lift of brushes, m	13
	Capacity of water tank, liters	2,000
	Capacity of water boiler, liters	2,200
MM ZIL-164A washing machine	Number of hoses	2
	Capacity of tank for special fluid, liters	70
	Capacity of working, tank, liters	45
	Capacity of drain tank, liters	50

Nomenclature	Brief Characteristics	
PAMA movable airport washing unit	Length of hoses, m	6
MA-7 special machine	Capacity of tanks, liters:	
	for wastes	1,200
	for water	500
	for chemical liquid	100
MA-8 special machine	Capacity of tanks, liters:	
	for wastes	2,000
	for water	600
	for chemical liquid	600
PP-1 electrical vacuum cleaner	Vacuum pressure, mm Hg	1,100
	Productivity, m^3/hr	440
	Weight, kg	180
E-000-000 electric vacuum cleaner	Vacuum pressure, mm Hg	1,300
	Productivity, m^3/hr	480
	Weight, kg	200

Appendix 3

Card "E"

For collection of data on the maintainability of aircraft of type ____________________ at airport ____________________

I. Name of maintenance operation with indication of the aircraft system, assembly, type of apparatus etc. (the name of the structural element is indicated in the description of the aircraft or in drawings) ____________________

____

II. General data:

1. Conditions of performing operation (hangar, dock, parking in the open, atmospheric conditions) ____________________

____

2. Date of performing operation and time of day (beginning and end of operation) ____________________

III. Characteristics of performing the maintenance operation:

1. Characteristics of the access conditions:

a) additional operations (indicate which elements of the structure have limited access) ______

____

____

____

____

b) number of service personnel ____________

c) time required to perform additional operations ____________

2. Characteristics of ease of removal:

a) number of service personnel performing operation ____

b) time required to perform dismantling operations ____

c) time required to perform assembly operations ____

d) tools used ____________

e) method of fastening the unit, article, structural element (indicate the name and number of fastening components) ____________

Reverse side of card "E" /195

3. Characteristics of interchangeability conditions:

a) brief description of adjusting operations (indicate the replaced component, apparatus or element by one or different series) ____________

b) number of service personnel performing the adjusting operations ____________

c) time required to perform adjusting operations ____

4. Characteristics of checkability:

a) brief description of addition operations performed during inspection of the unit, apparatus, connection or structural element ____________

b) apparatus and attachments used ______________________

____

____

c) number of service personnel performing additional operations ____

____

d) length of time required to perform additional operations ____

e) length of time required to perform main operations __

____

IV. Additional data and suggestions ______________________

____

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Signature of person filling out card ______________________

______________ ______________ 197_.

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Card "R"

For collection of data on the technological effectiveness of repairing aircraft of type ____________________ at plant No. ________ of Civil Aviation.

I. Name of technological repair operation with indication of the aircraft system, assembly, type of apparatus, etc. (indicate the name of the structural elements in the description of the aircraft or in drawings) ____

____

II. General data:

1. Identification mark and plant No. of aircraft ____________
2. Hours of accrued flight time since beginning of operation

____

III. Characteristics of performing operations:

1. Characteristics of access conditions:
   a) preparation and finishing operations (indicate what interferes with access) ________________

____

____

____

   b) number of service personnel performing the preparation and finishing operations ____________________________
   c) time required to perform preparatory and finishing operations ____

____

d) tools used (type and nomenclature)________________

____

____

2. Characteristics of ease of removal:
   a) number of service personnel performing operation____
   b) time required to perform disassembly operations_____
   c) time required to perform assembly operations________
   d) tools used (type and nomenclature)________________

____

   e) method of fastening the unit, apparatus or element (indicate the name and number of fastening components)______________________________

____

____

____

Reverse side of card "R" /197

3. Characteristics of interchangeability conditions:
   a) brief description of adjusting operations (indicate the changed component, apparatus or element by one or different series)____________________

____

   b) number of service personnel performing the adjusting operations____________________________________

____

   c) time required for adjusting operations____________
   d) tools used (type and nomenclature)________________

____

4. Characteristics of checkability:
   a) brief description of additional operations performed during inspection of the assembly, apparatus, connection or element___________________________

____

b) apparatus and attachments used ____________________

____

c) number of service personnel and length of time re-required to perform the main operations ____________

____

d) number of service personnel and length of time required to perform additional operations ________________

____

5. Repairability.

If the component (assembly) belongs to the first category, indicate the name and reason for replacement (unable to repair, failure, completion of operation life etc). ___

____

IV. Additional data and suggestions ____________________

____

Signature of person filling out card ________________________

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SYMBOL LIST

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P_T - idle times for maintenance and repair

P_s - idle times in operable condition

P_r - idle times during performance of flight

K_r - readiness coefficient

K_{tu} - technical utilization coefficient

$\omega(t)$ - failure rate

K_{or} - coefficient of operational readiness

K_{op} - utilization coefficient

W_{aft} - annual accrued flight time of aircraft (degree of annual utilization)

D_n - average length of non-stop flight

t_{day} - assumed daily time reserve for completing flights

t_{ST} -idle time of aircraft at airports between contiguous flights

T - mean-cycles-between failures

t_r - average recovery time

μ - rate of correcting failures

K_e - structural economy in manufacture and operation

K_T - specific labor expenditures for maintenance and repair

K_{sp} - specific expenditures for materials and spare parts

K_{mr} - specific idle times during maintenance and repair

K_o - specific idle times in an operable condition at home airport

K_p - specific idle times during performance of flight

$P\{\tau<t_d\}$ - probability of completing repair within time τ, not exceeding the given time

t_d - scheduled idle time of aircraft

K_a - coefficient of accessibility

K_d - coefficient of ease of removal

K_i - coefficient of interchangeability

K_K - coefficient of checkability

K_c - coefficient of continuity

G - weight of aircraft structure

G_e - weight of empty aircraft without engines

A - total operating life of aircraft

M_c - repair cycle operating life of aircraft

M_e - repair cycle operating life of engine

M_a - repair cycle operating life of apparatus

K_{ec} - coefficient of engine replacement ahead of schedule

n_e - number of engines on aircraft

K_{ai} - coefficient of replacement of i-th apparatus ahead of schedule

n_{ai} - number of apparatus of i-th type on aircraft

$F_w(Z)$ - function of maintainability

$\mathcal{F}_w(Z)$ - loss function

$f_w(Z)$ - distribution density of random value

C_n - cost of new aircraft /199

P_{to} - probability of routine takeoff of aircraft at established time

P_d - probability of delay in takeoff of aircraft

K_{TC} - specific labor expenditures for maintenance and repair of aircraft (without engines)

K_{td} - specific labor expenditures for maintenance and repair of engine

K_{ea} - specific expenditures for materials and spare parts for aircraft (without engines)

K_{ee} - specific expenditures for materials and spare parts for engine

C_o - total expenditures for materials and spare parts during M_c

C_p - expenditures for materials and spare parts during major overhaul of aircraft

C_e - expenditures for materials and spare parts during major overhaul of engine

C_{ai} - expenditures for materials and spare parts during major overhaul of i-th apparatus

D_i - coefficient of comparative analysis of maintainability according to i-th indicator

K_{1000} - number of failures of apparatus per 1000 hours of accrued flight time of the aircraft

r - correlation coefficient

r_d - directive value of correlation coefficient

REFERENCES

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1. Bazovskiy, I. Nadezhnost'. Teoriya i praktika (The Theory and Practice of Reliability). Moscow, Mir, 1965, 373 pages.

2. Barzilovich, Ye.Yu. The Problem of Servicing Complex Technical Systems. Izvestiya AN SSSR, Tekhnicheskaya kibernetika, No. 6, 1966, pp. 73-85.

3. Barlou, R. and F. Proshan. Matematicheskaya teoriya nadezhnosti (The Mathematical Theory of Reliability). Moscow, Sovetskoye radio, 1969, 488 pages.

4. Bodyagin, A.A. and Ye.A. Ovrutskiy. Proyektirovaniye passazhirskikh samoletov s uchetom ekonomiki ekspluatatsii (Designing Passenger Aircraft with Consideration of Operational Economy). Moscow, Mashinostroyeniye, 1964, 295 pages.

5. Volkov, P.N. The Problem of Repairability Indicators. In the book: Nadezhnost' i kontrol' kachestva (Reliability and Quality Control). Collection of Articles No. 9, Moscow, Izdatel'stivo standartov, 1969, pp. 3-14.

6. Gnedenko, B.V. Kurs teorii veroyatnostey (A Course in Probability Theory). Moscow, Fizmatgiz, 1961, 400 pages.

7. GOST 13377-67 Nadezhnost' v tekhnike. Terminy (Reliability in Engineering. Terminology). Moscow, Izdatel'stivo standartov, 1968, 15 pages.

8. Gradshteyn, I.S. and I.M. Ryzhik. Tablitsy integralov, summ, ryadov i proizvedeniy (Table of Integrals, Sums, Series and Products). Moscow, Fizmatgiz, 1962, 1100 pages.

9. Grigor'yev, V.P. Vzaimozamenyayemost' agregatov v samoletostroyenii (The Interchangeability of Apparatus in Aircraft Construction). Moscow, Mashinostroyeniye, 1968, 258 pages.

10. Dunin-Barkovskiy, I.V. and N.V. Smirnov. Teoriya veroyatnostey i matematicheskaya statistika v tekhnike (obshchaya chast') (Probability Theory and Mathematical Statistics in Engineering (General Part)). Moscow, Gostekhizdat, 1955, 556 pages.

11. Kalabro, S.R. Principles and Practical Problems of Reliability. Translated from the English. Moscow, Mashinostroyeniye, 1966, 376 pages.

12. Cox, D.R. and W.L. Smith. Renewal Theory. Translated from English. Moscow, Sovetskoye radio, 1967, 299 pages.

13. Korn, G.A. and T.M. Korn. Mathematics Handbook. Translated from English, Moscow, Nauka Press, 1968, 720 pages.

14. Kredentser, B.P. and M.M. Lastovchenko et al. Resheniye zadach nadezhnosti i ekspluatatsii na universal'nykh ETsVM (Solving Reliability and Operational Problems on Universal Digital Computers). Moscow, Sovetskoye radio, 1967, 400 pages.

15. Metodicheskiye polozheniya po otsenke kachestva izdeliy mashinostroyeniya (Procedural Aspects of Analyzing the Quality of Machine-Building Articles). No. 1, Moscow, Izdatel'stvo standartov, 1968, 28 pages.

16. Ovcharov, L.A. Prikladnyye zadachi teorii massovogo obsluzhivaniya (Applied Problems of Queueing Theory). Moscow, Mashinostroyeniye, 1969, 324 pages.

17. Osnovy ekspluatatsii radioelektronnoy apparatury (Fundamentals of Operating Radioelectronic Equipment). V.Yu. Lavrinenko, Editor. Moscow, Vysshaya shkola, 1968, 320 pages.

18. Pugachev, A.I., M.L. Burakov and N.T. Domotenko et al. Tekhnicheskaya ekspluatatsiya letatel'nykh apparatov (Technical Operation of Aircraft). Moscow, Transport, 1969, 480 pages.

19. The Repairability of Electronic Equipment. Collection of articles translated from English. Moscow, Sovetskoye radio, 1964, 430 pages. /201

20. Rumshinskiy, L.Z. Elementy teorii veroyatnostey (Fundamentals of Probability Theory). Moscow, Nauka Press, 1970, 254 pages.

21. Sveshnikov, A.A. Prikladnyye metody teorii sluchaynykh funktsiy (Applied Methods of the Theory of Random Functions). Moscow, Nauka Press, 1968, 464 pages.

22. Seyfi, T.F., A.I. Yaroshenko and V.I. Bakayev. Garantiya vysokogo kachestva — Sistema KANARSPI (High Quality Warranty — The KANARSPI System). Moscow, Izdatel'stvo standartov, 1968, 147 pages.

23. Serov, A.V. Diagnostika — osnova ekspluatatsionnoy nadezhnosti mashin (Diagnosis as the Basis of the Operational Reliability of Machines). Moscow, Znaniye, 1969, 34 pages.

24. Smirnov, N.V. and I.V. Dunin-Barkovskiy. Kurs teorii veroyatnostey i matematicheskoy statistiki dlya tekhnicheskikh prilozheniy (A Course in Probability Theory and Mathematical Statistics for Engineering Applications). Moscow, Nauka Press, 1969, 511 pages.

25. Smirnov, N.N. and A.V. Chalov. The Kinetics of Failures and Postrepair Reliability of Components of Special Aircraft Equipment. Transactions of the State Scientific Research Institute, State Archives, No. 58, Moscow, Department of Scientific and Technical Information, 1969, pp. 1-18.

26. Smirnov, N.N. Tekhnicheskoye obsluzhivaniye i remont samoletov za rubezhom (Maintenance and Repair of Aircraft Abroad). Moscow, Redizdat, Ministry of Civil Aviation, 1968, 108 pages.

27. Smirnov, N.N. Voprosy remontoprigodnosti mashin (Problems of the Repairability of Machines). Moscow, Znaniye, 1970, 96 pages.

28. Smirnov, N.N. Ekspluatatsionnaya tekhnologichnost' samoletnyk konstruktsiy (The Maintainability of Aircraft Structures). Moscow, Oborongiz, 1963, 125 pages.

29. Stepanov, S.V. The Frequency of Preventive Maintenance. Trudy VVIOLKA imeni prof. Zhukovskogo N.Ye., No. 1222, 1968.

30. Feller, V. Vvedeniye v teoriyu veroyatnostey i yeye prilozheniya (Introduction of Probability Theory and Its Applications). Vol. 2, Moscow, Mir, 1967, 752 pages.

31. Shekunov, Ye.P. Osnovy tekhnologicheskogo chleneniya konstruktsii samoleta (Fundamentals of Dividing an Aircraft Structure Into Technological Parts). Moscow, Mashinostroyeniye, 1968, 166 pages.

32. Shirokov, A.M. Osnovy nadezhnosti i ekspluatatsii elektronnoy apparatury (Fundamentals of the Reliability and Operation of Electronic Equipment). Minsk, Nauka i tekhnika, 1965, 266 pages.

33. Shiskonok, N.A. and M.M. Lastovchekno. Basis for the Frequency of Performing Preventive Maintenance. Trudy Kiyevskogo vysshego inzhenernogo radiotekhnicheskogo uchilishcha, No. 34, 1963.

34. Shteyn, B.Ye. and M.Ye. Shteyn. The Problem of Locating the Components of Complex Systems. Izvestiya AN SSSR — Tekhnicheskaya kibernetika, No. 1, 1970, pp. 42-49.

35. Aeroplane, Vol. 113, No. 2905, June 1967, pp. 15-22.

36. AIAA Paper, No. 267, 1968, p. 7.

37. Air Transport World, No. 9, 1966, pp. 67 and 70-72.

38. Air Transport World, No. 10, 1968, pp. 43-46.

39. Aircraft Structure Sampling Inspection Program, FAA Maintenance Simposium, Continued Reliability of Transport-Type Aircraft Structure, Washington, D.C., November 1966, 30 pages.

40. American Aviation. Vol. 30, No. 8, 1967, pp. 79-81.

41. American Aviation. Vol. 32, No. 13, 1968, pp. 42-45.

42. A Review of the Economic Situation of Air Transport 1957-1967, ICAO Circular, No. 89-AT/15, 1967, 83 pages.

43. Aviation Week and Space Technology, September 18, 1967, pp. 33-37.

44. Call I.I. Maintenance Policies for Stochastically Failing Equipment. Management Science, Vol. 11, No. 5, 1965, pp. 493-524.

45. FAA Present and Future Philosophy in Regulating Aircraft Structural Maintenance Programs, Washington, November, 1966, 5 pages.

46. Journal of the Aeronautical Society of India, No. 2, 1967, pp. 33-44.

47. Management Consideration of Reliability and Maintainability Program Requirements for a 1980 Jet Transport. AIAA Paper, No. 68-201, 10 pages.

48. SAE Journal, Vol. 73, No. 4, 1965, pp. 54-58.

49. Standard Method of Estimating Comparative Direct Operating Costs of Turbine Powered Transport Airplanes, October 1967.

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